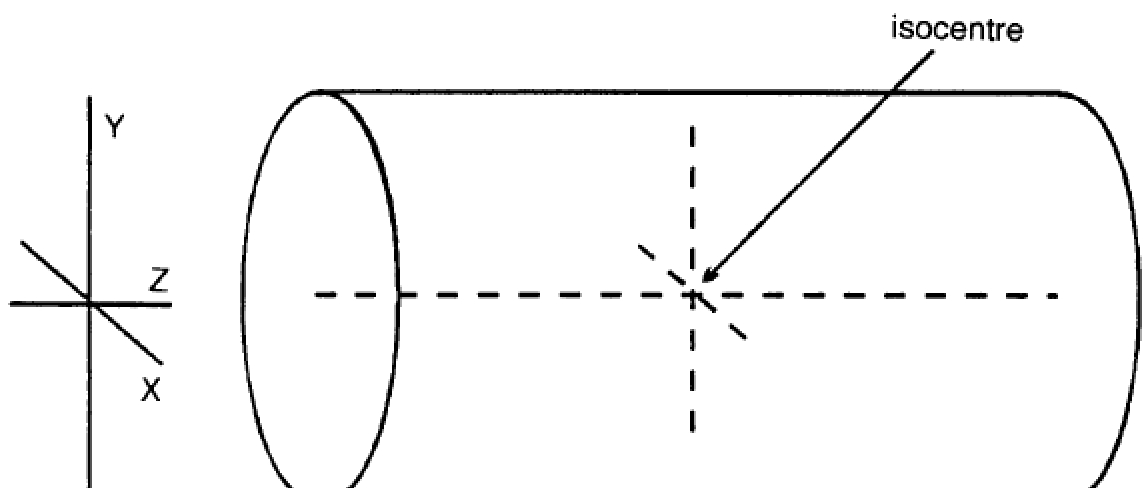
Spatial encoding and image formation

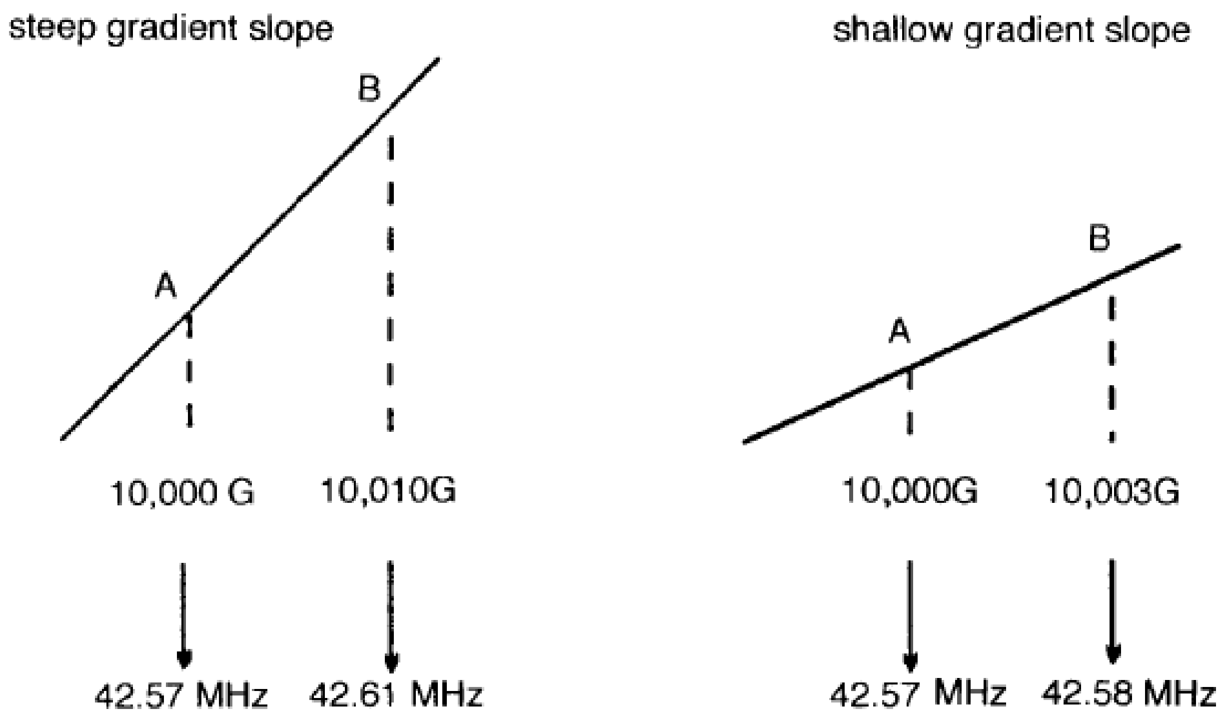
Spatial encoding and Gradients

Position along gradient	Field strength	Larmor frequency
at isocentre	10 000 G	42.5700 MHz
1 cm negative to isocentre	9 999 G	42.5657 MHz
2 cm negative to isocentre	9 998 G	42.5614 MHz
1 cm positive to isocentre	10 001 G	42.5742 MHz
2 cm positive to isocentre	10 002 G	42.5785 MHz
10 cm negative to isocentre	9 990 G	42.5274 MHz

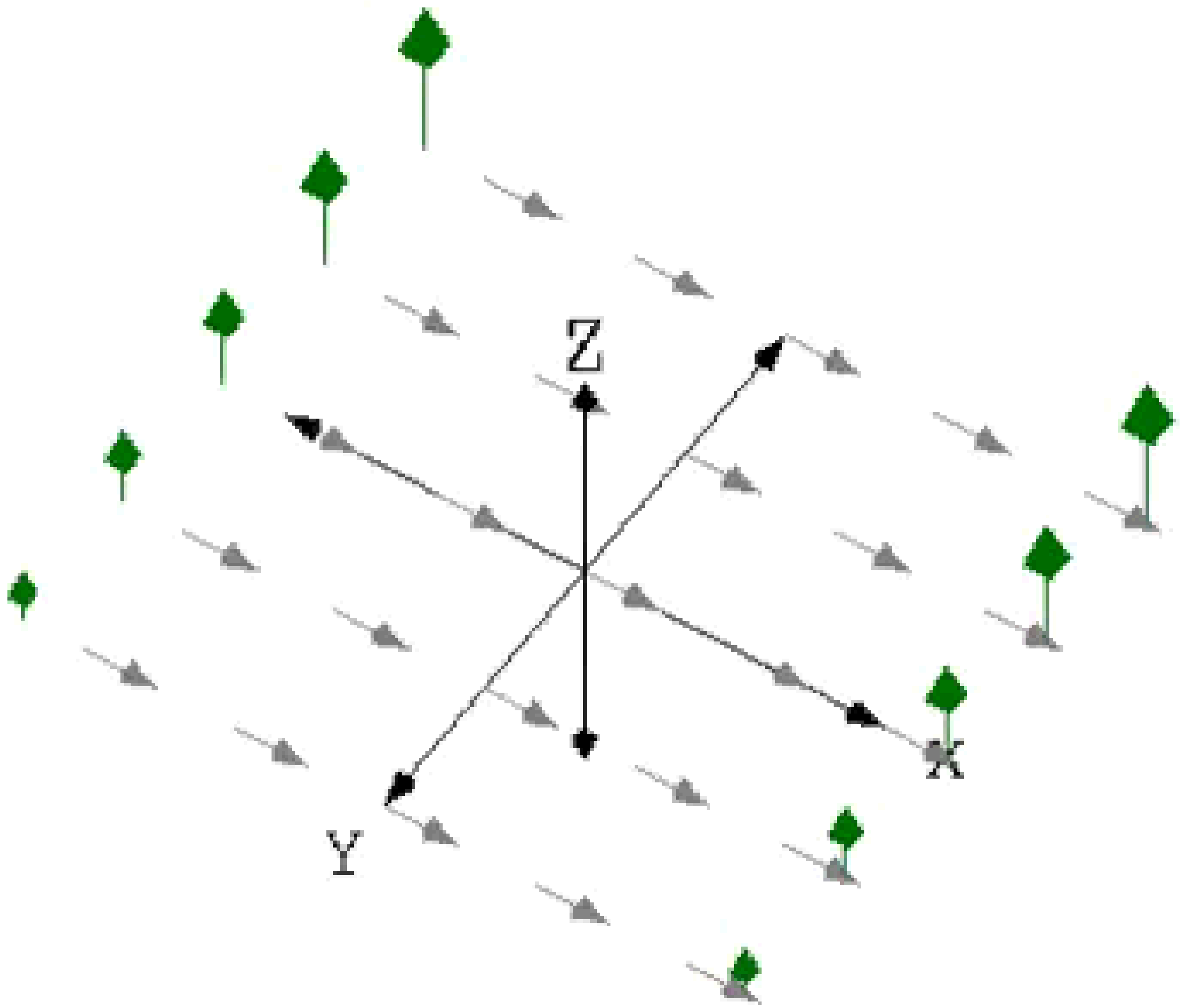
- **Number of gradients:**
  - Three gradient coils situated within the bore of the magnet, named according to the axis of their action:
    - Z *gradient*
    - Y *gradient*
    - X *gradient*
- **Magnetic isocentre:**
  - The centre point of the axis of all three gradients → The magnetic field strength remains unaltered here even when the gradients are applied.



- **The gradient slope = gradient amplitude:**
  - The rate of change of the magnetic field strength along the gradient axis
  - Steep gradient slopes alter the magnetic field strength and precessional frequency more than shallow gradient slopes.



N.B: 1.0 T is equal to 10 000 G

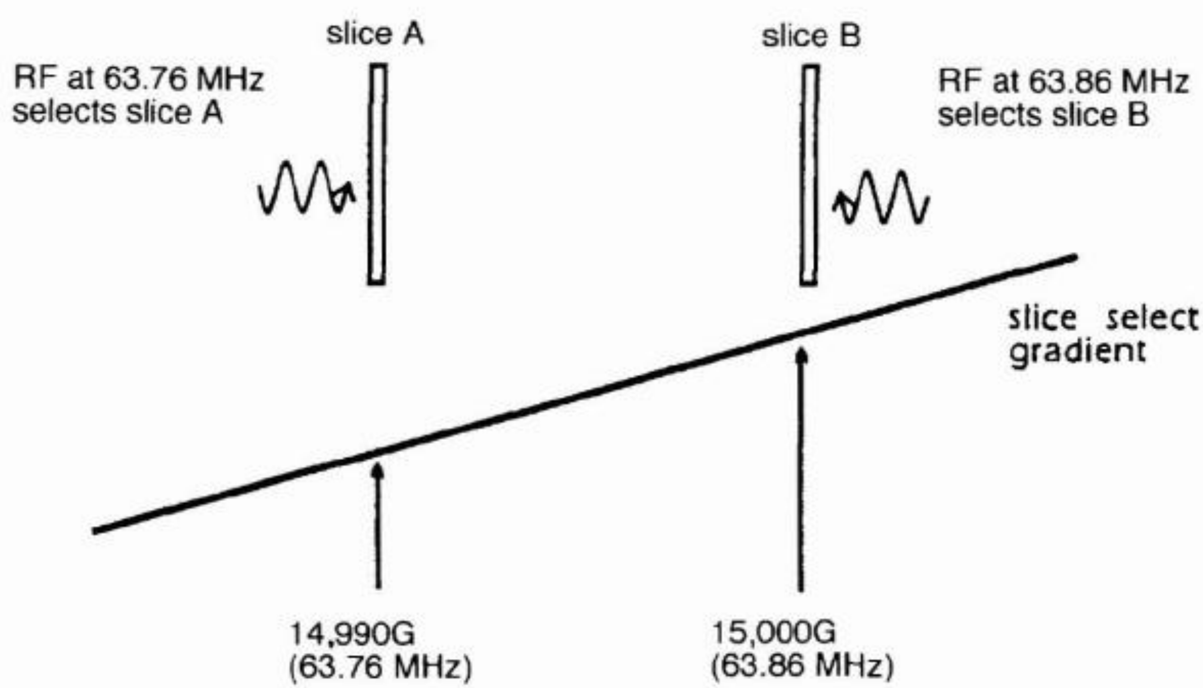

Z
Y
X

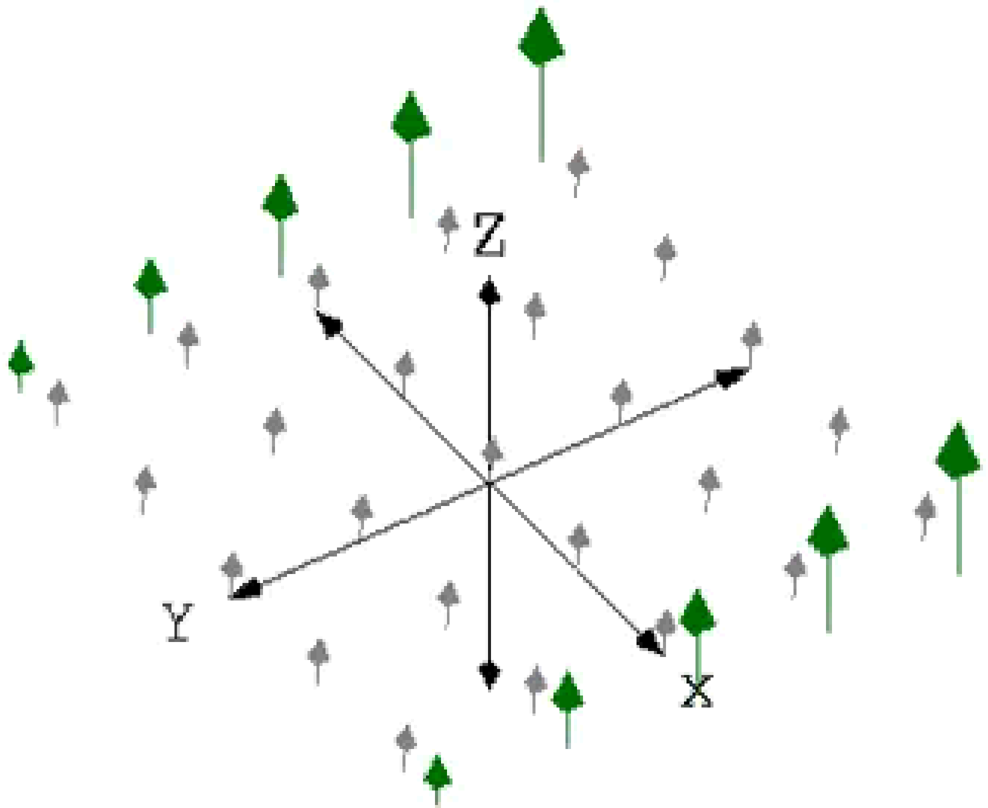
Gradients perform the following tasks:

1) Slice selection gradient:

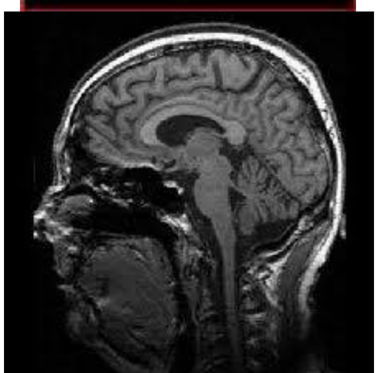
Mechanism of slice selection:

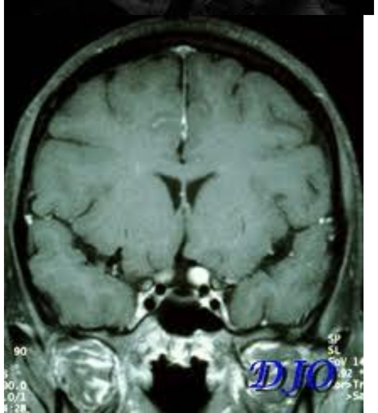
- Specific point along the axis of the gradient has a specific precessional frequency → A slice situated at a certain point along the axis of the gradient has a particular precessional frequency
- A slice can be selectively excited, by transmitting RF with a band of frequencies coinciding with the Larmor frequencies of spins in a particular slice defined by the slice select gradient.
- Nuclei situated in other slices do not resonate.

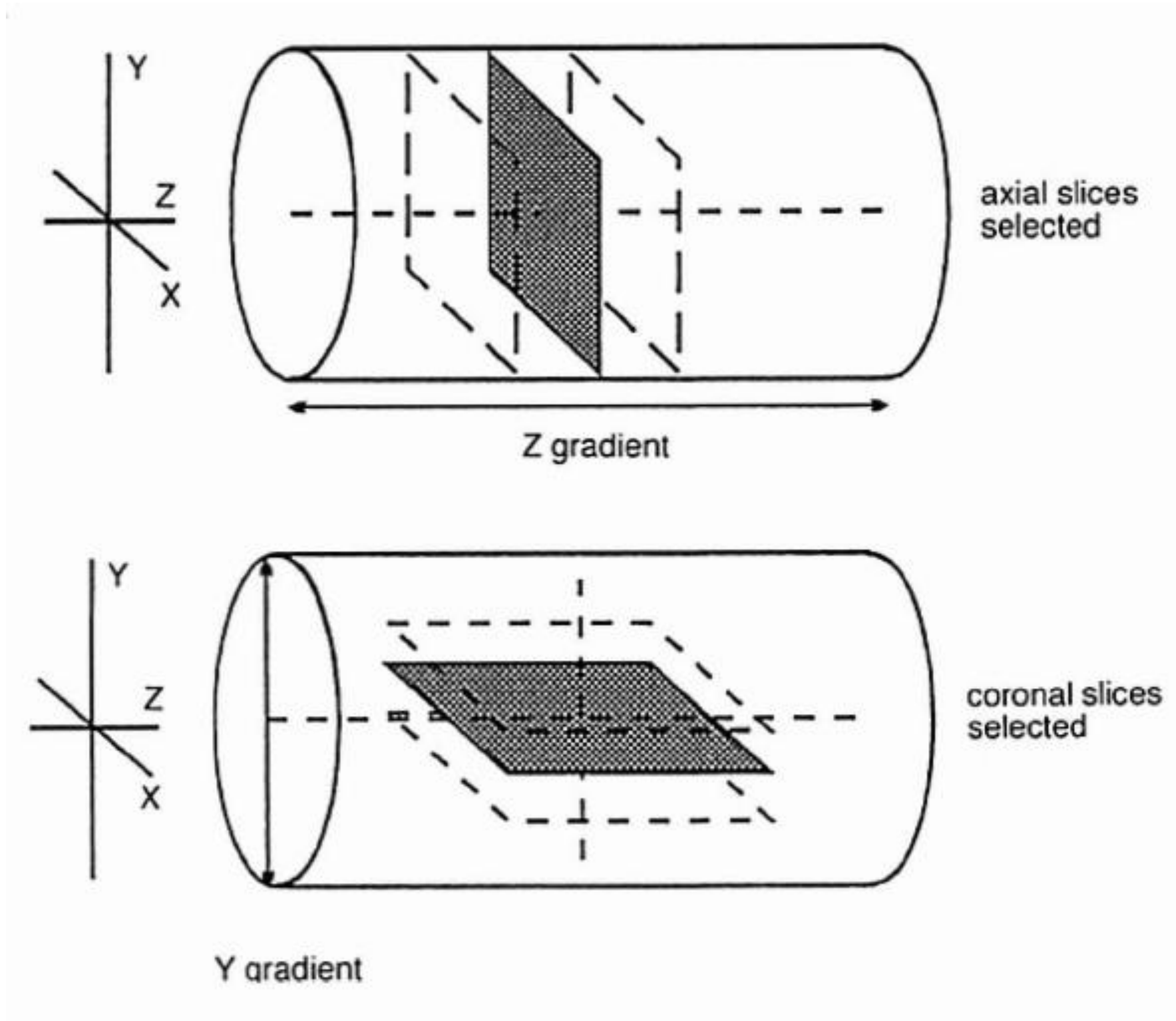



Z
Y
X

- The Z *gradient* selects *axial slices.*
- The X *gradient* selects *sagittal slices.*
- The Y *gradient* selects *coronal slices.*
- Oblique slices are selected using two gradients in combination.

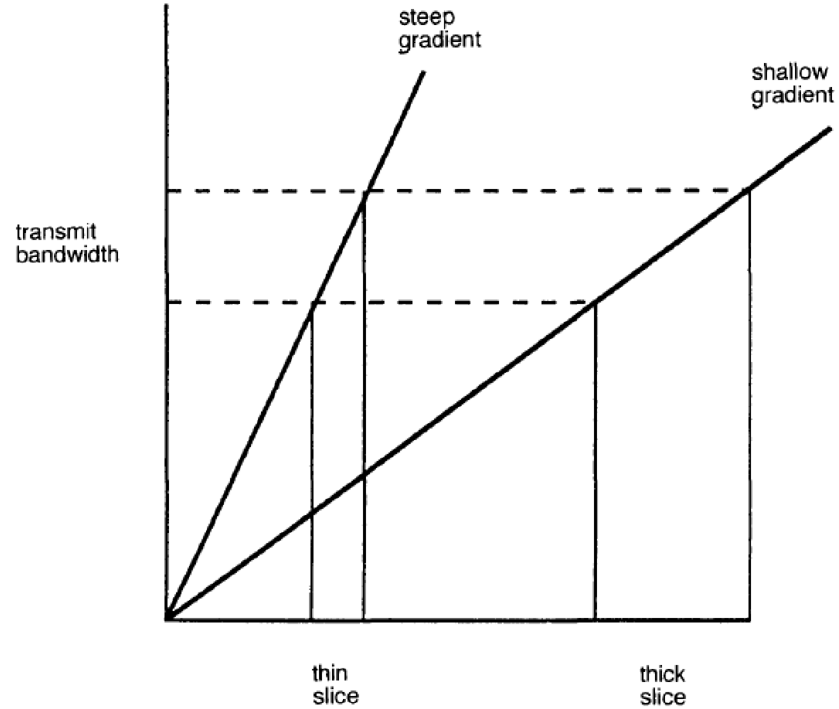






Slice thickness depends on:

1) Transmit bandwidth:
   - RF frequency range transmitted to excite the slice (contain a range of frequencies to match the difference in precessional frequency between two points)
2) Gradient slope:
   - Steep gradient slopes result in a large difference in precessional frequency between two points
   - Shallow gradient slopes result in a small difference in precessional frequency between the same two points.

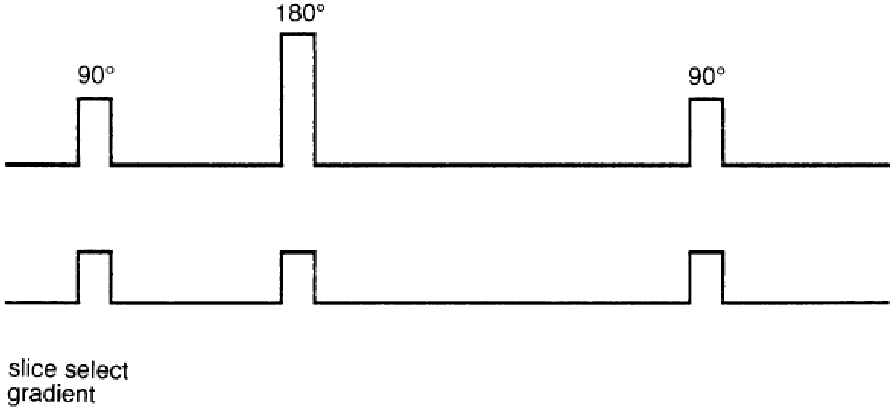


To achieve *thin slices: Steep slice select slope &/or narrow bandwidth*
To achieve *thick slices: Shallow slice select slope &/or broad transmit bandwidth*

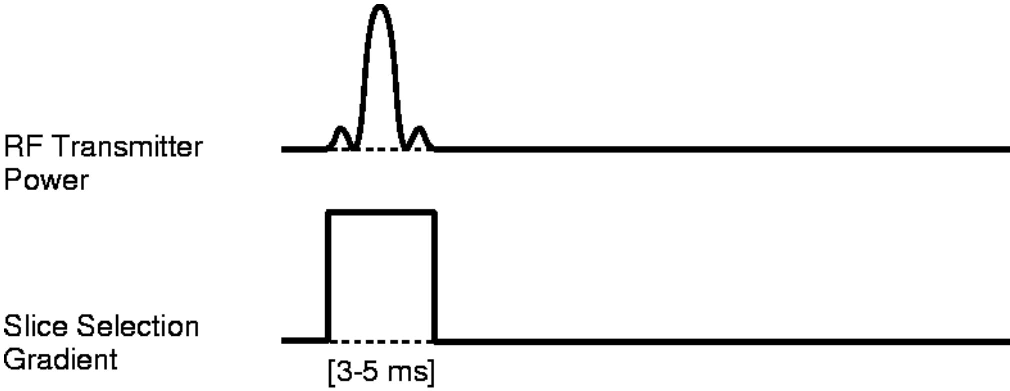
N.B: Gap between the slices is also determined by the gradient slope and by the thickness of the slice. The size of the gap is important in reducing image artefact.

Timing of application of slice selection gradient:

- In spin echo pulse sequences:
  - Slice select gradient is switched on during the application of the 90º excitation pulse and during the 180º rephasing pulse (to excite and rephase each slice selectively)

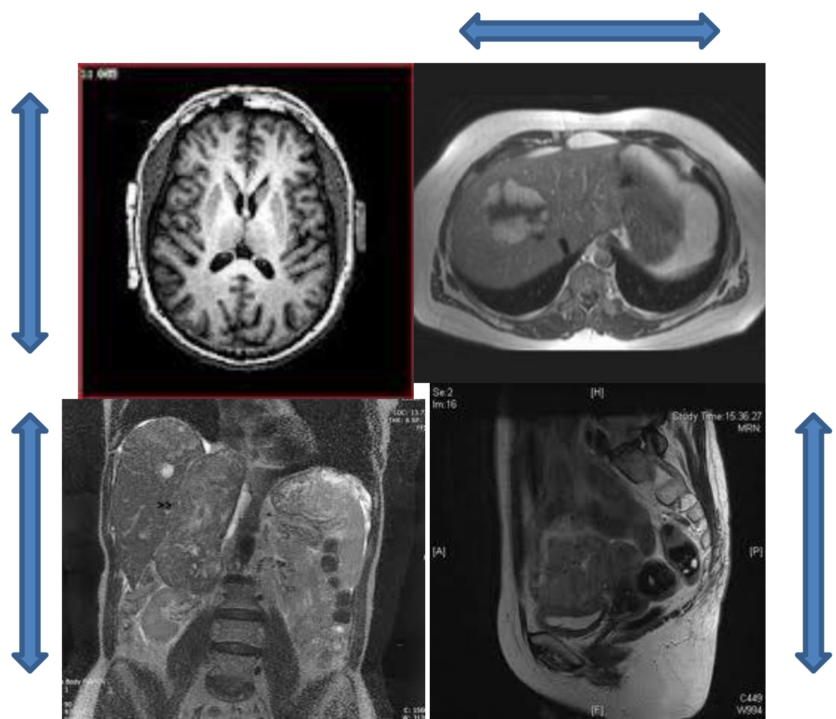


- In gradient echo pulse sequences:
  - The slice select gradient is switched on during the excitation pulse only.



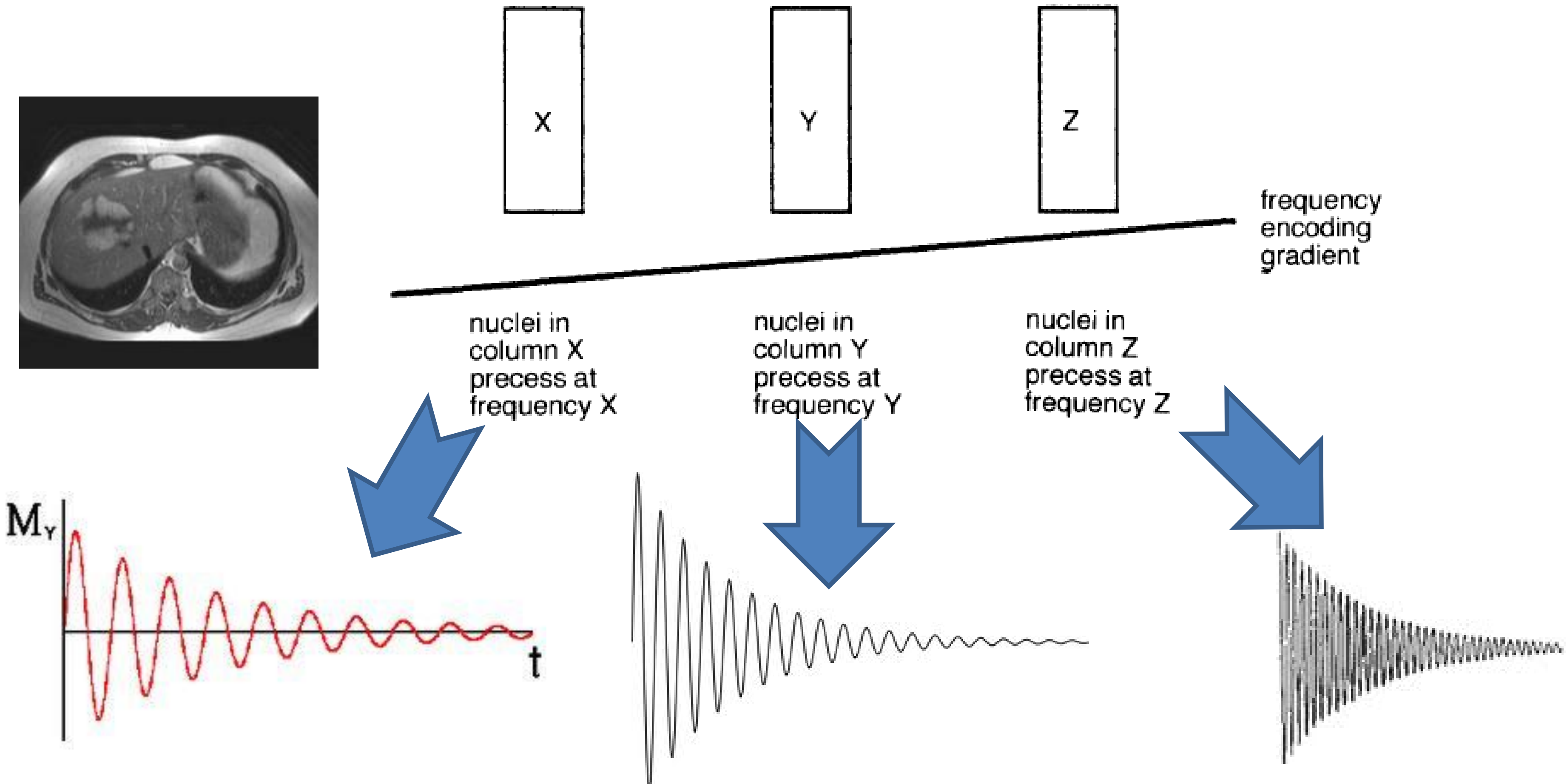
2) Frequency encoding gradient:

- Once a slice has been selected, the signal coming from it must be located along both axes of the image.
- The signal is usually located along the **long axis of the anatomy** by frequency encoding.



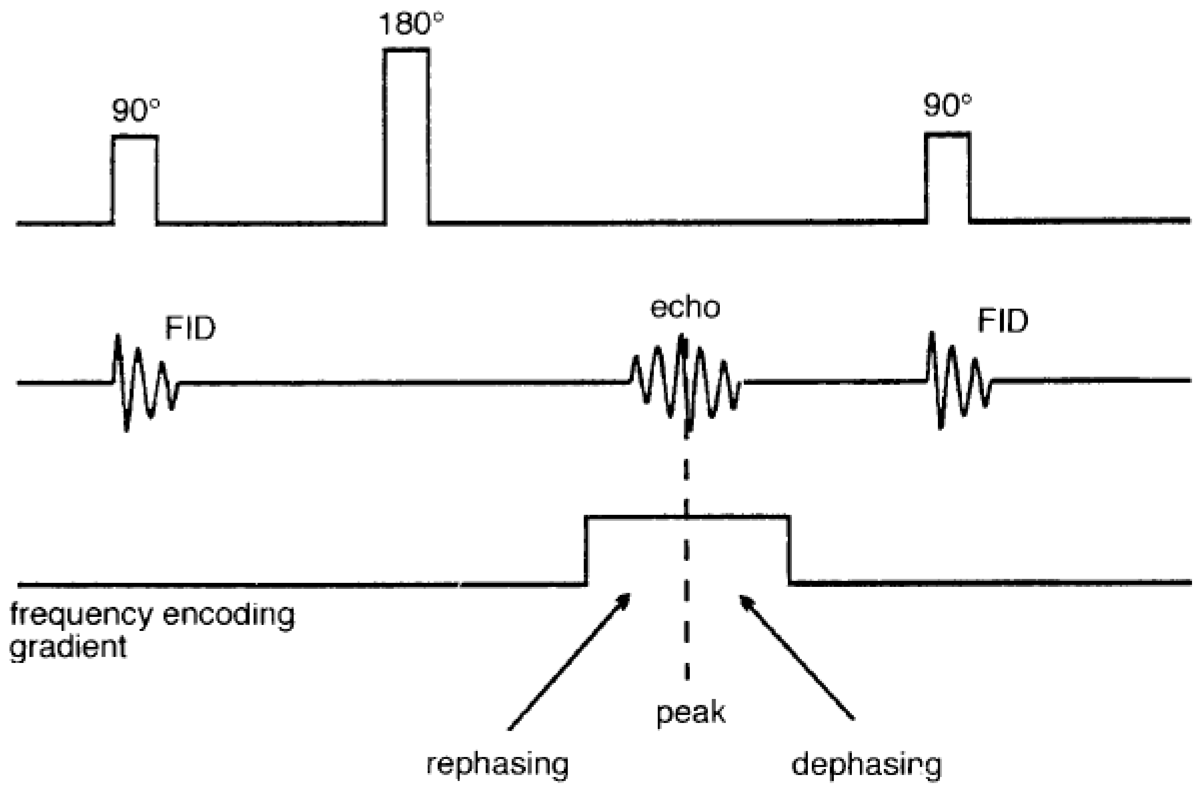
<u>*Mechanism:*</u>

- When the frequency encoding gradient is switched on, the magnetic field strength (& precessional frequency) is altered in a linear fashion→ production of a frequency difference (shift) of signal along its axis.
- The signal can now be located according to its frequency.



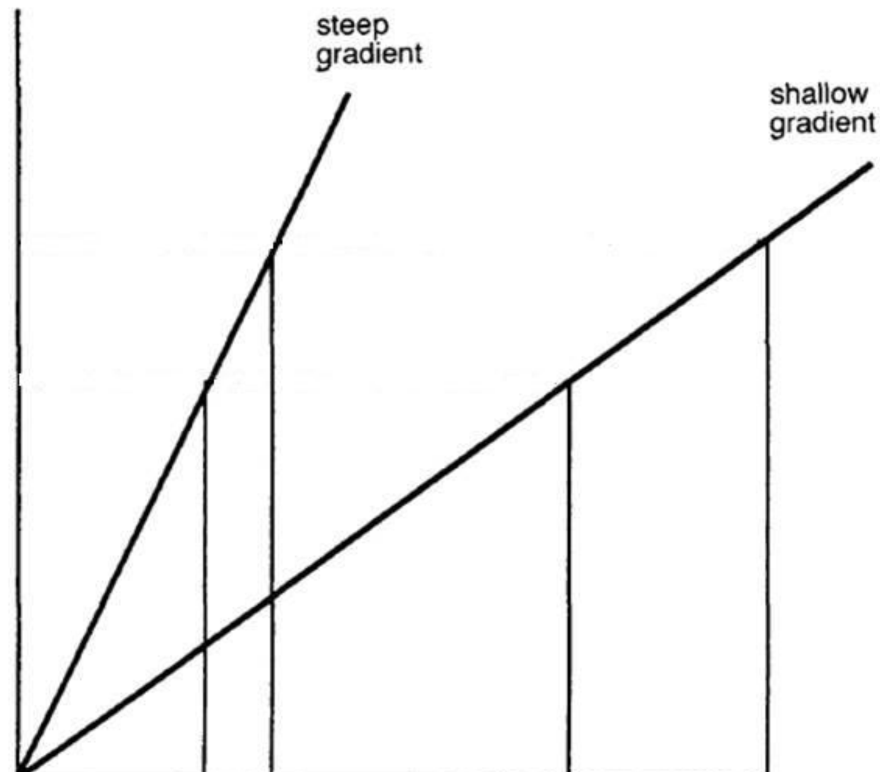
Timing of frequency encoding gradient:

- The frequency encoding gradient is switched on when the signal is received (called: *readout gradient)* .
- *i.e.* gradient is switched on during the rephasing and dephasing part of the echo
- *Echo* peak *is* centered in the middle of the frequency encoding gradient



Field of view (FOV) across frequency encoding direction:

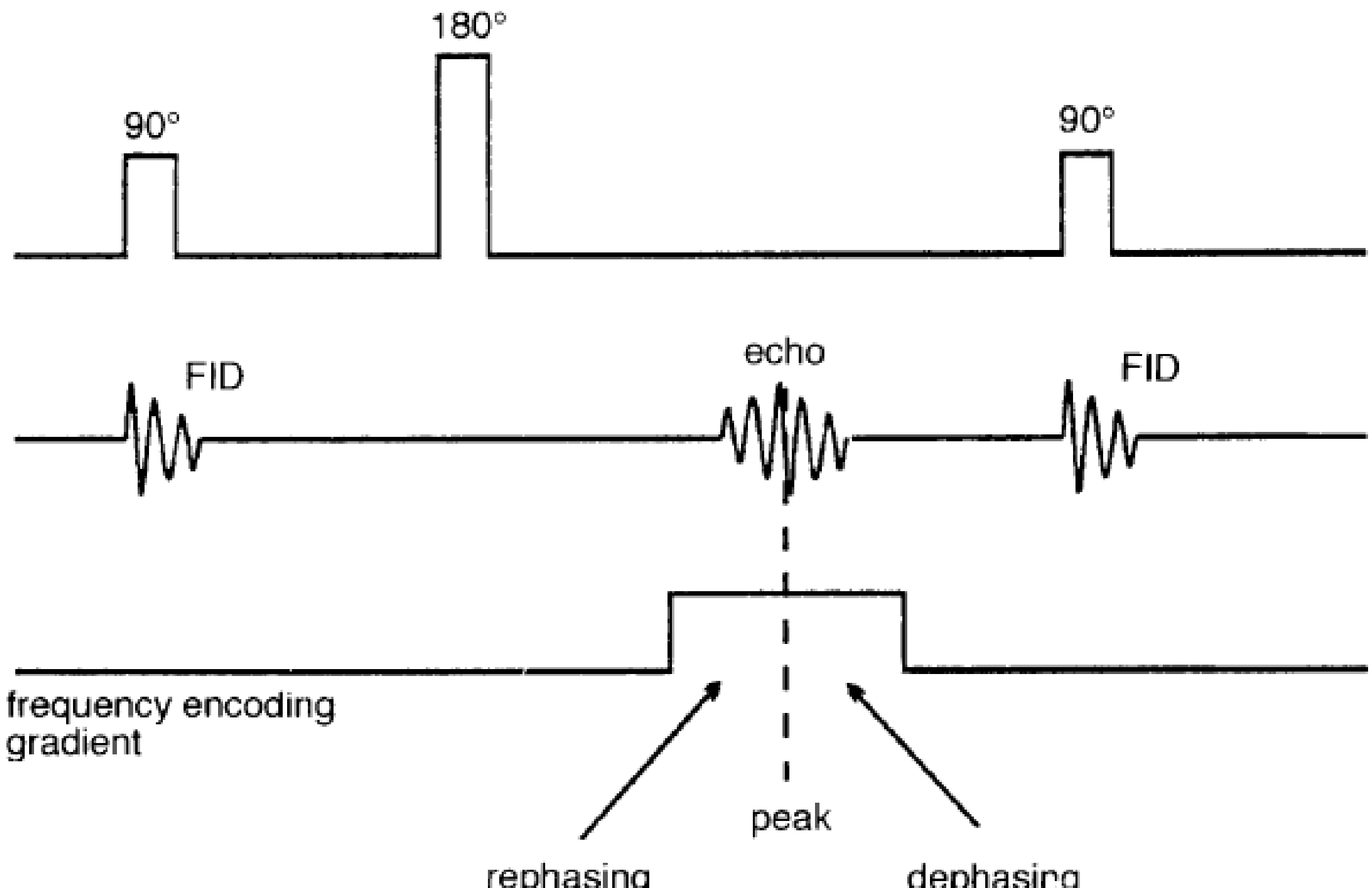
- The steepness of the slope of the frequency encoding gradient determines the size of the anatomy covered along the frequency encoding axis during the scan (*FOV).*
- increase of steepness → decrease of FOV



Definitions related to frequency encoding gradient:

A. Sampling time:

Duration of the frequency encoding gradient during readout

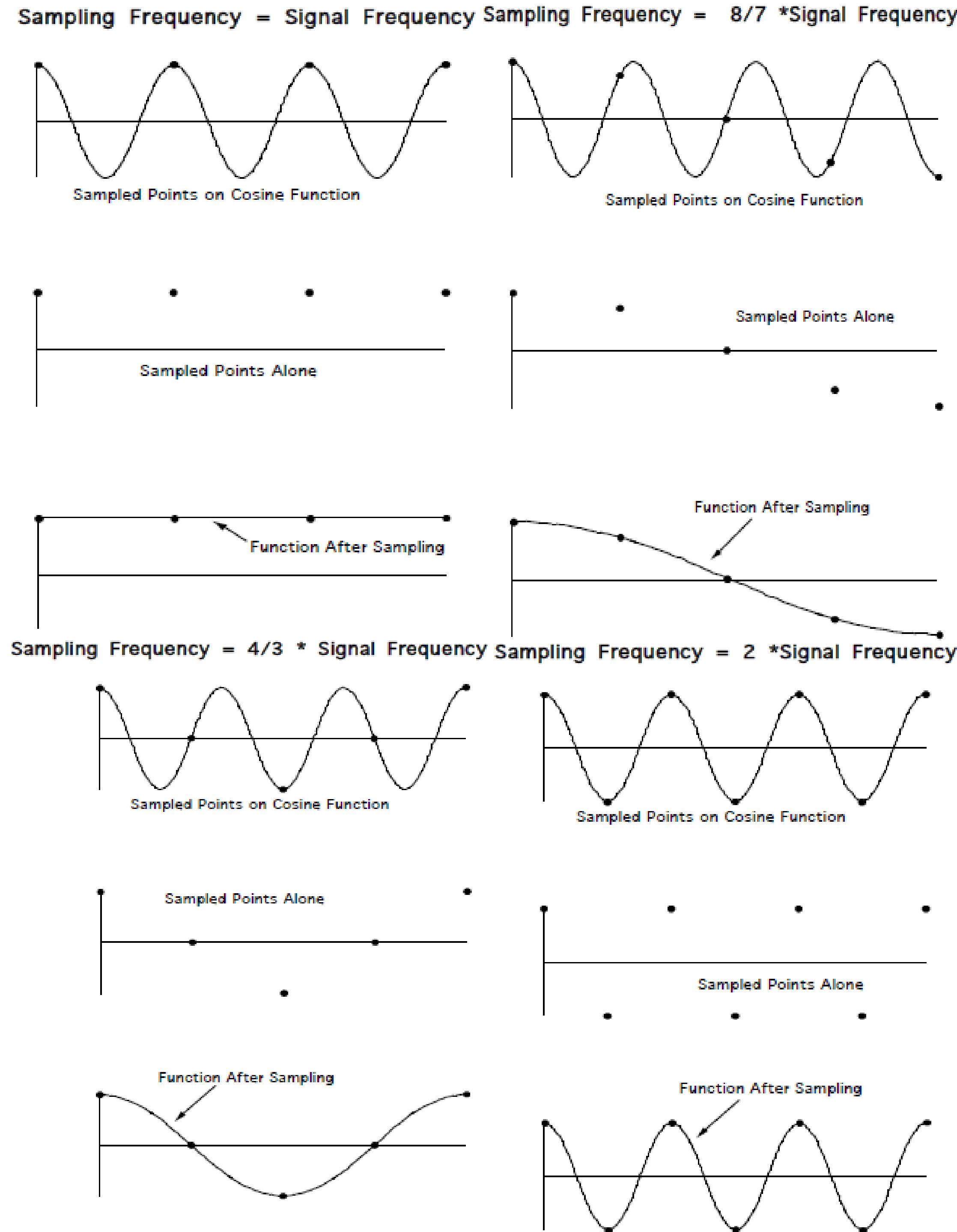


B. Sampling rate:

Rate at which the samples are taken during readout.

C. The Nyquist theorem:

Any signal must be sampled at least twice per cycle in order to reproduce it accurately



D. Receive bandwidth:

Range of frequencies accepted by the receiver to sample the MR signal

E. Final number of samples:

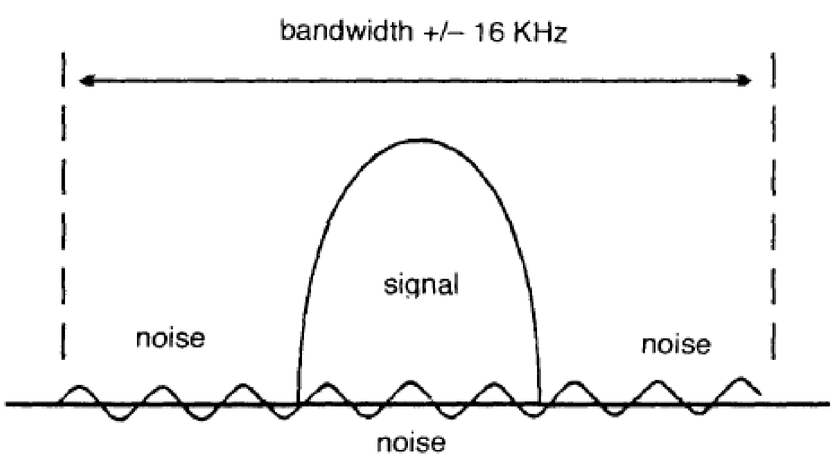
= number of pixels in frequency encoding direction = Sampling Rate/BW

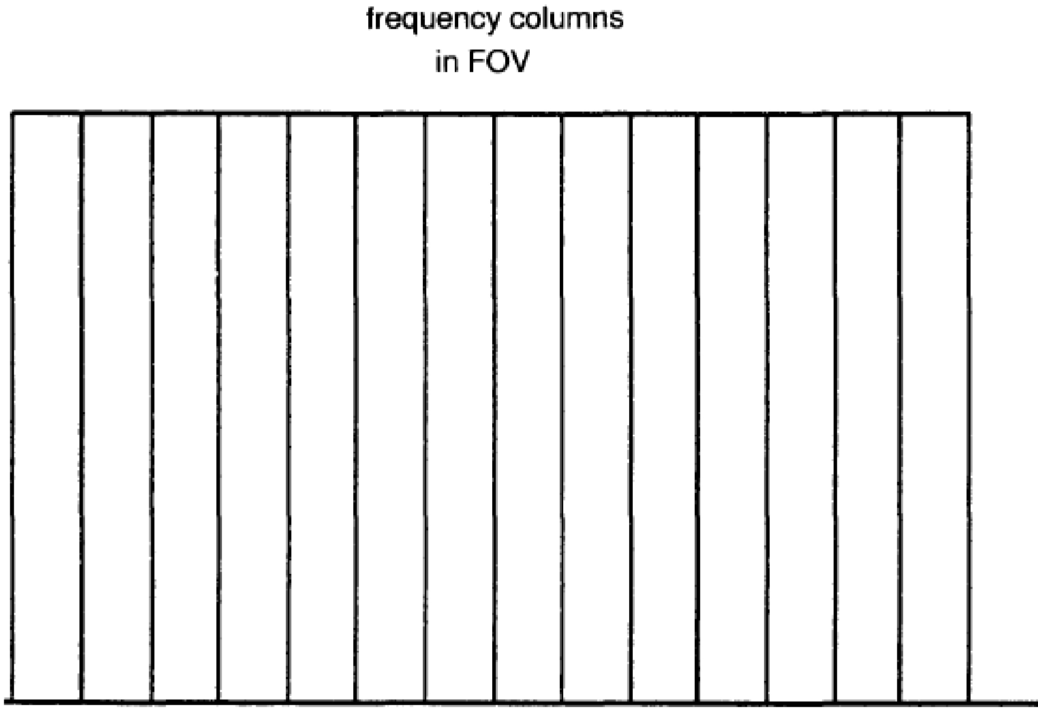
Note:

- _Sampling rate is proportional to the receive bandwidth._
- _Sampling time is inversely proportional to:_

  (1) the sampling rate,

  (2) the receive bandwidth.

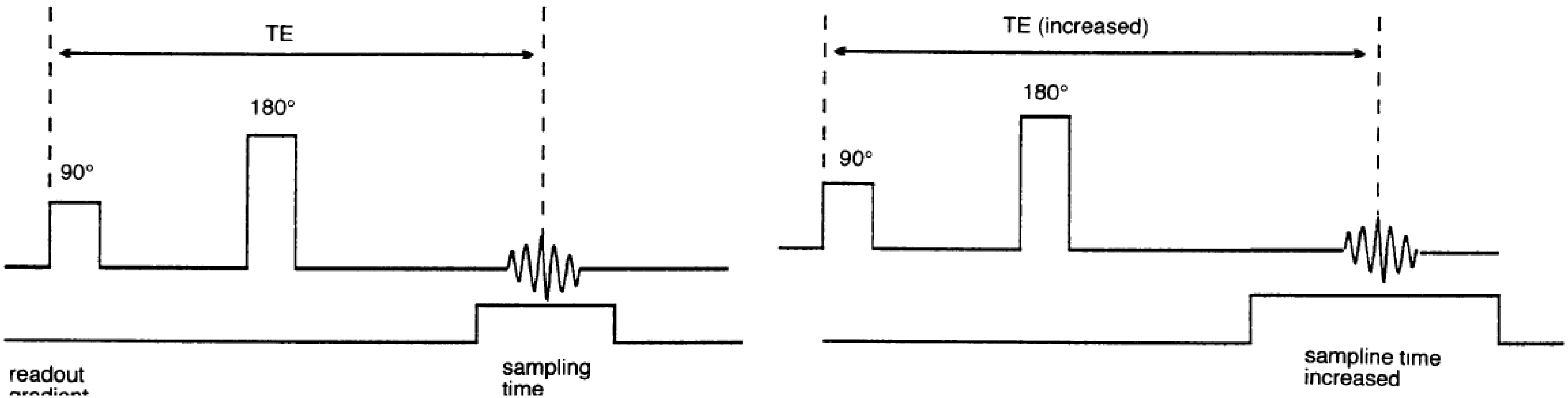




__Important note:__

↓ Receive bandwidth → ↑ sampling time → ↑minimum TE because

Explanation: the echo is centered on the middle of the frequency encoding gradient.

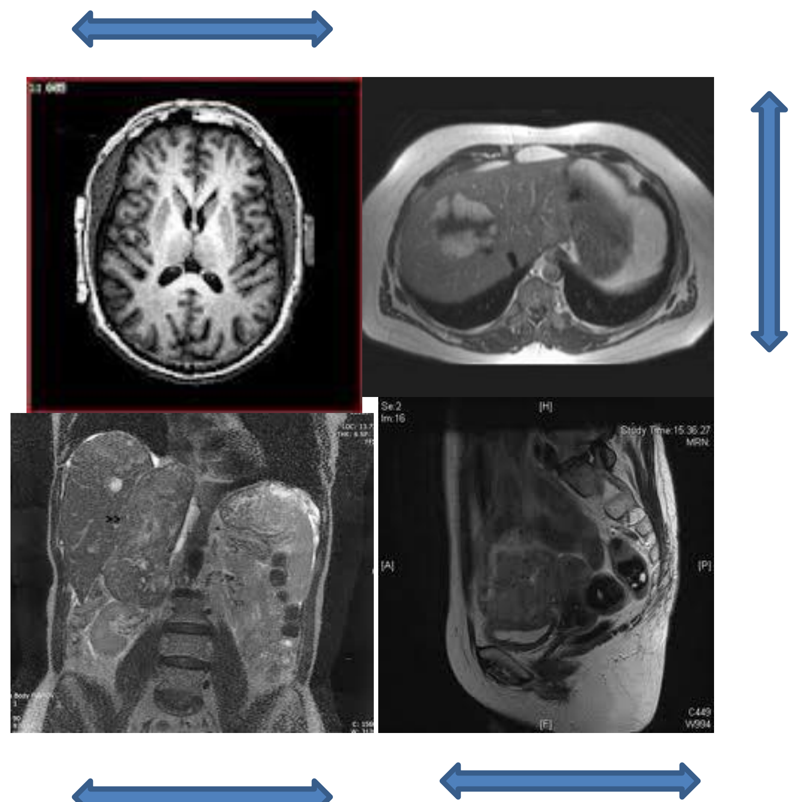


Under normal circumstances the receive bandwidth and sampling time are fixed.

However, there are occasions when it is desirable to increase receive bandwidth (when decreasing TE become desirable)

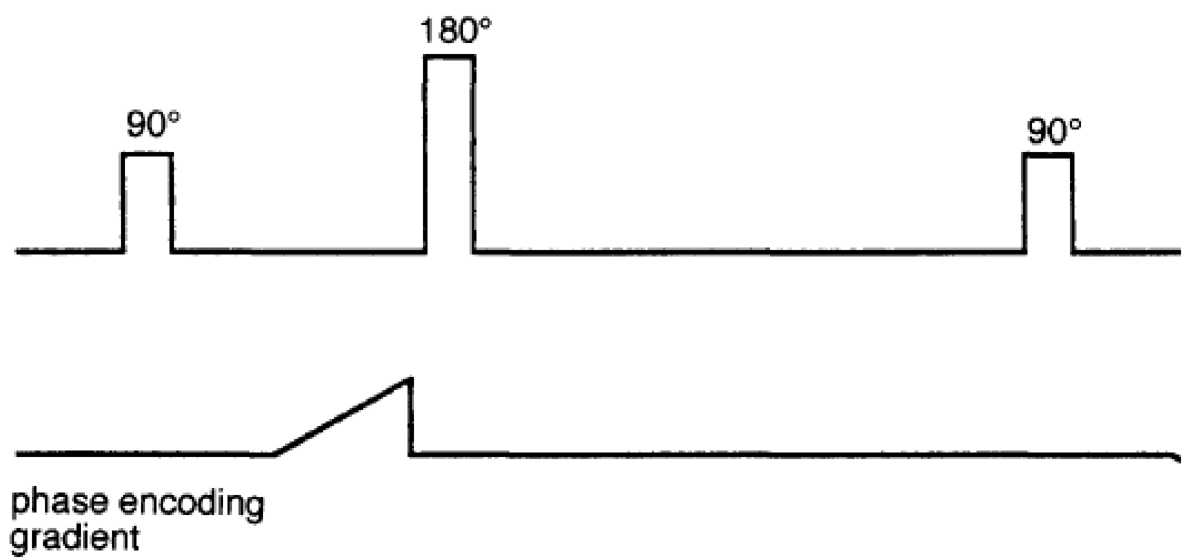
3) Phase encoding gradient:

- Locate the signal is along horizontal axis of the image



Timing:

The phase encoding gradient is usually switched on just before the application of the 180^{o} rephasing pulse and then switched off

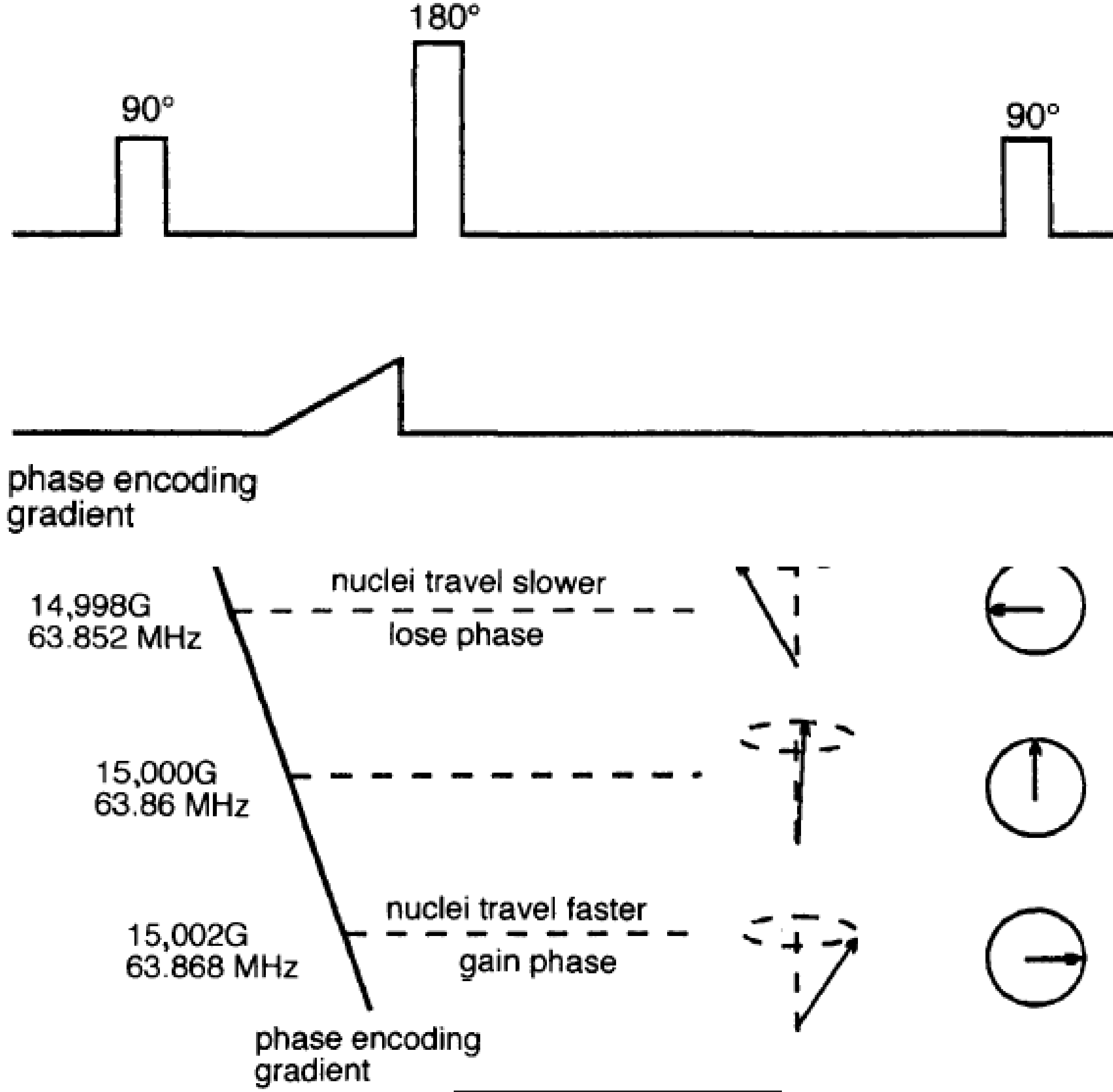


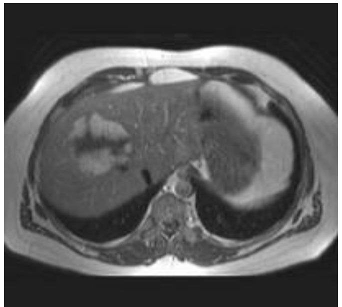
Mechanism:

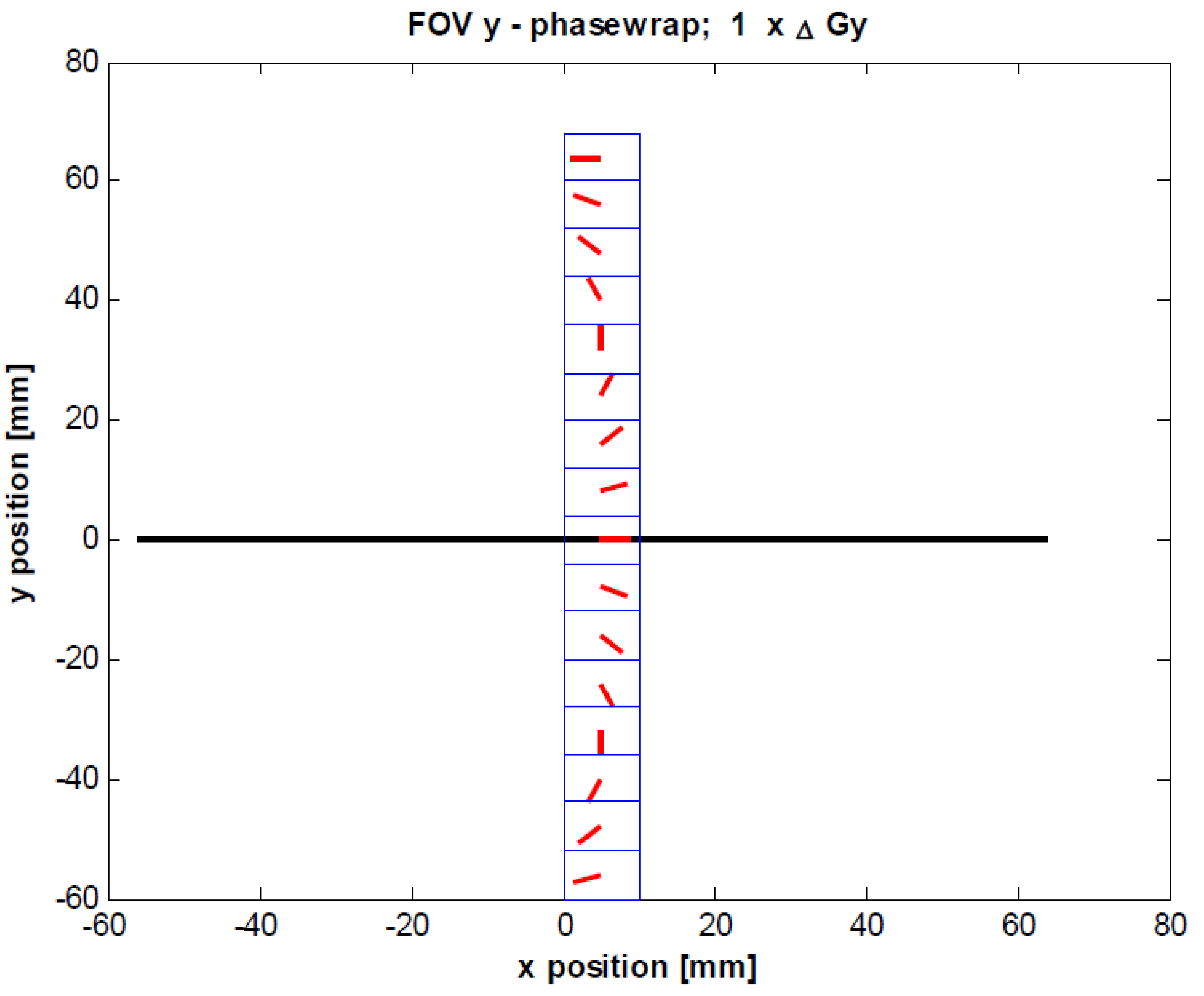
- Switched on phase encoding gradient →magnetic field strength (& precessional frequency) along gradient axis is altered.
- Switched off phase encoding gradient → magnetic field strength = Bo again ,& precessional frequency= Larmor frequency again
- However, the phase difference between the nuclei remains

i.e. same speed, but different positions.

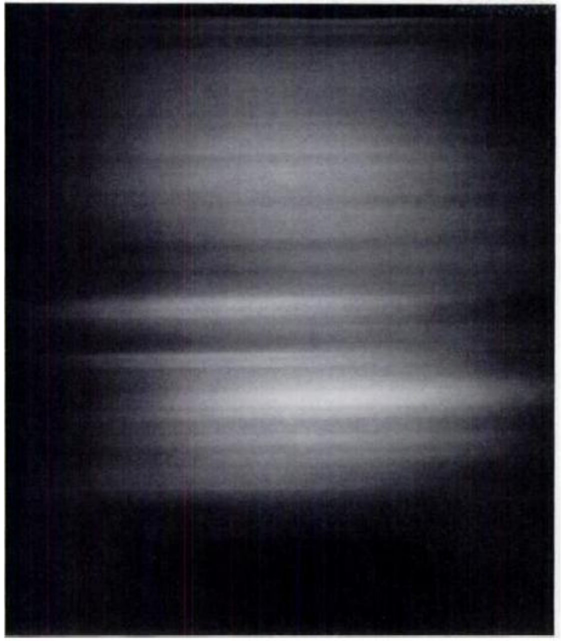
- This difference in phase between the nuclei is used to determine their position along the phase encoding gradient.







So that image can be formed with one phase encoding only .....BUT



2 phase encoding steps.

4 phase encoding steps.

8 phase encoding steps.

12 phase encoding steps.

16 phase encoding steps.

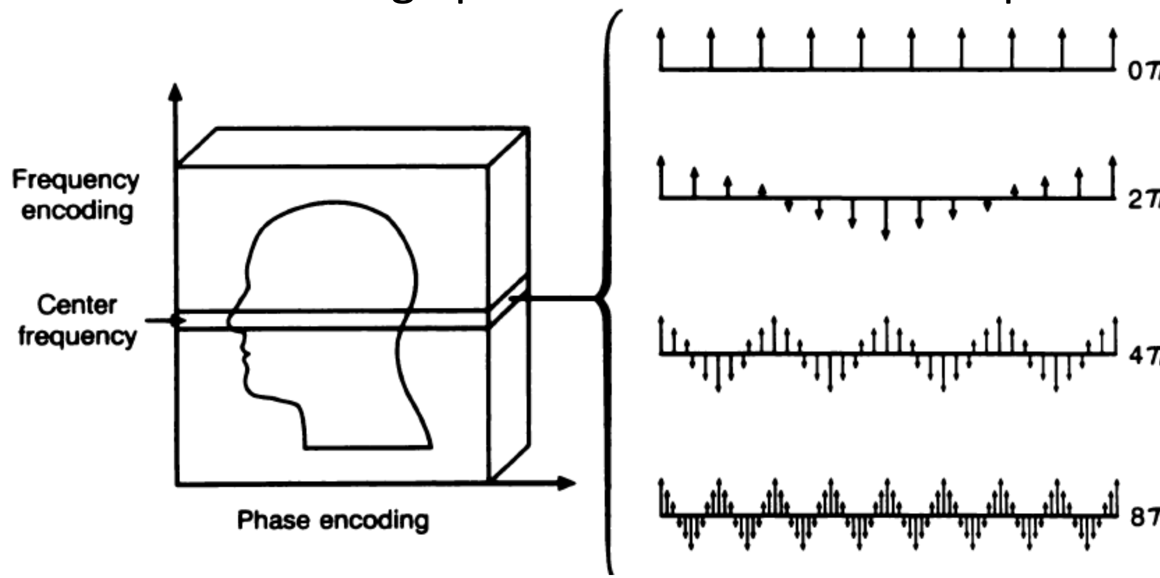
24 phase encoding steps.

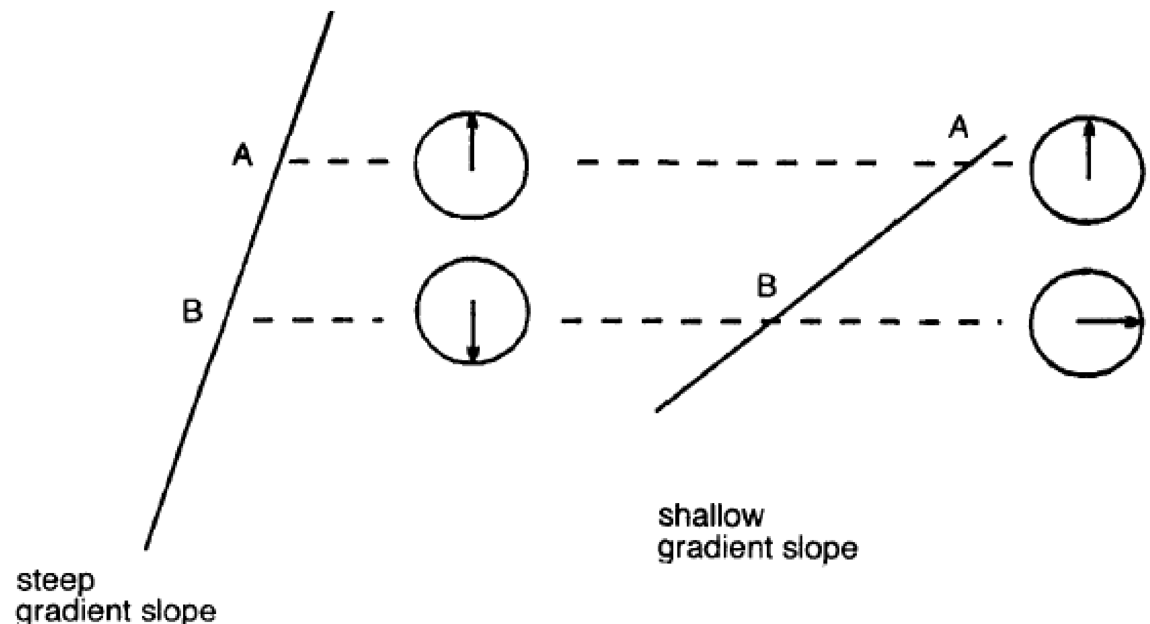
with 32 phase encoding steps.

48 phase encoding steps.

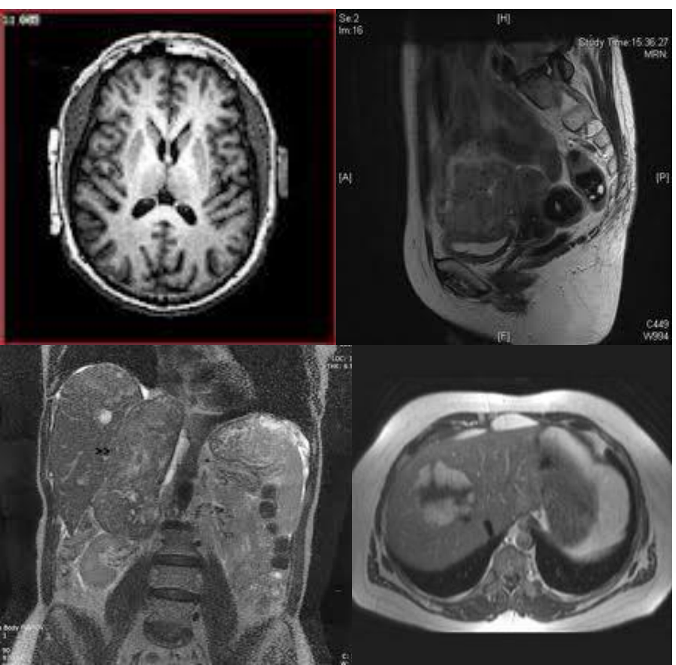
N.B:

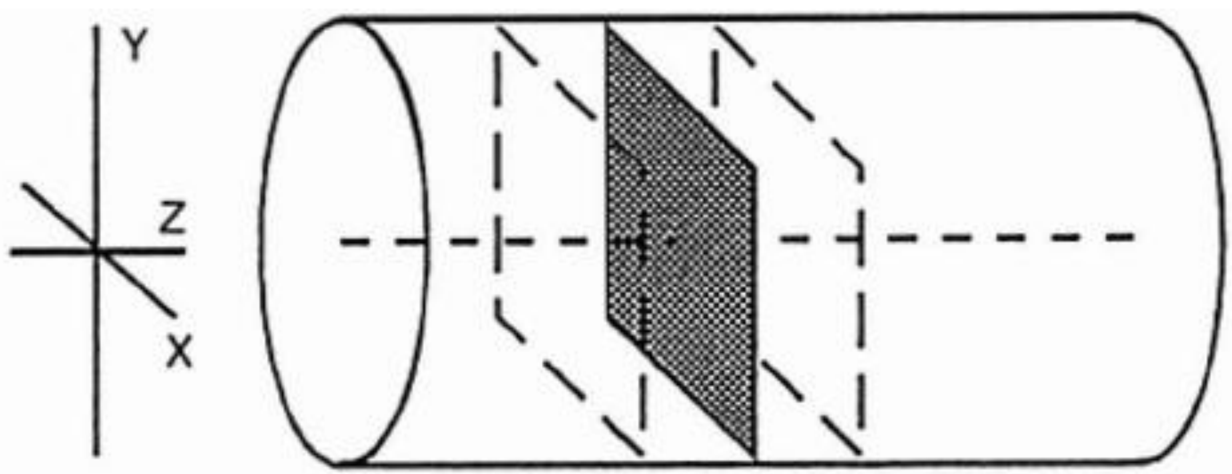
1) Ideally , number of phase encoding gradients applied must be = number of pixel in the phase direction, each time with a different slope
2) A steep phase encoding gradient causes a large phase shift between two points along the gradient



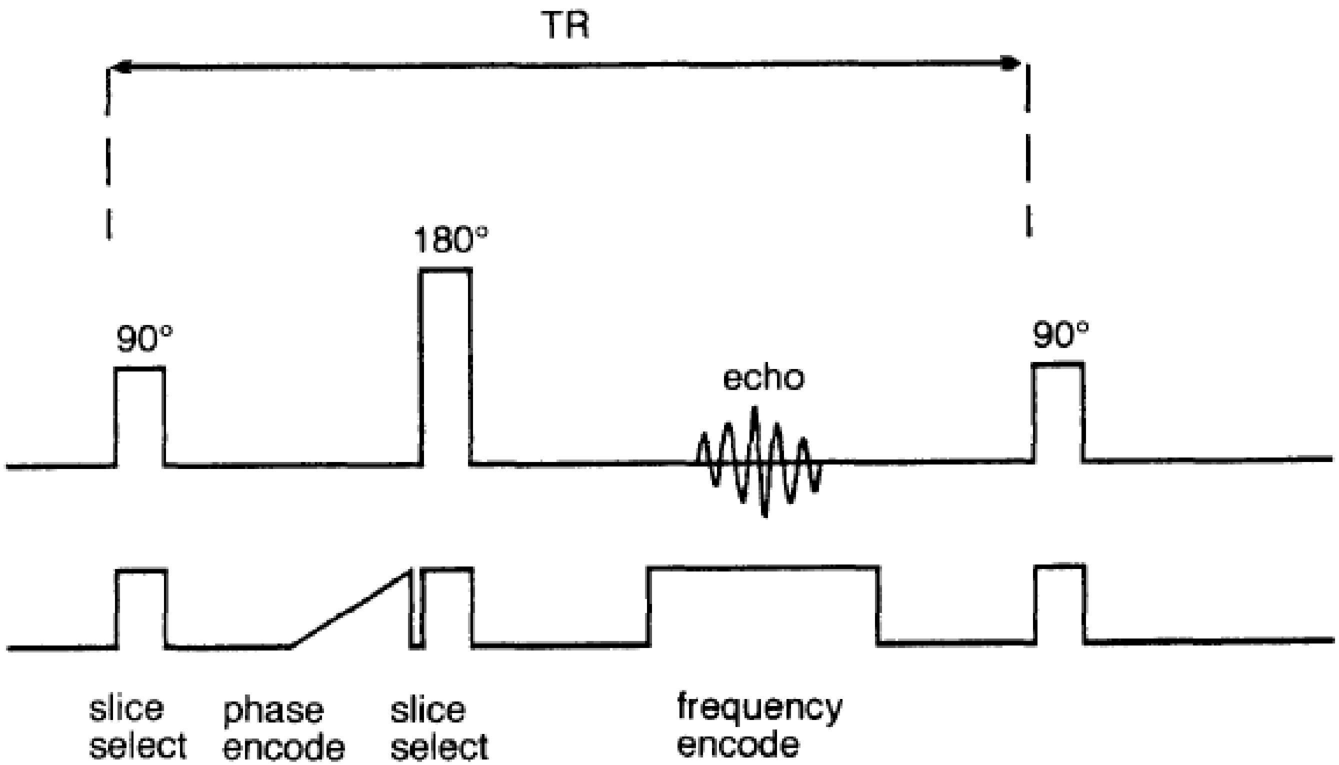


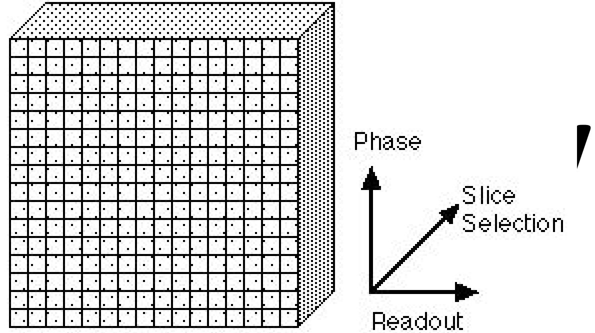
	Slice selection	Phase encoding	Frequency encoding
Sagittal	X	Y	Z
Axial (body)	Z	Y	X
Axial (head)	Z	X	Y
Coronal	Y	X	Z

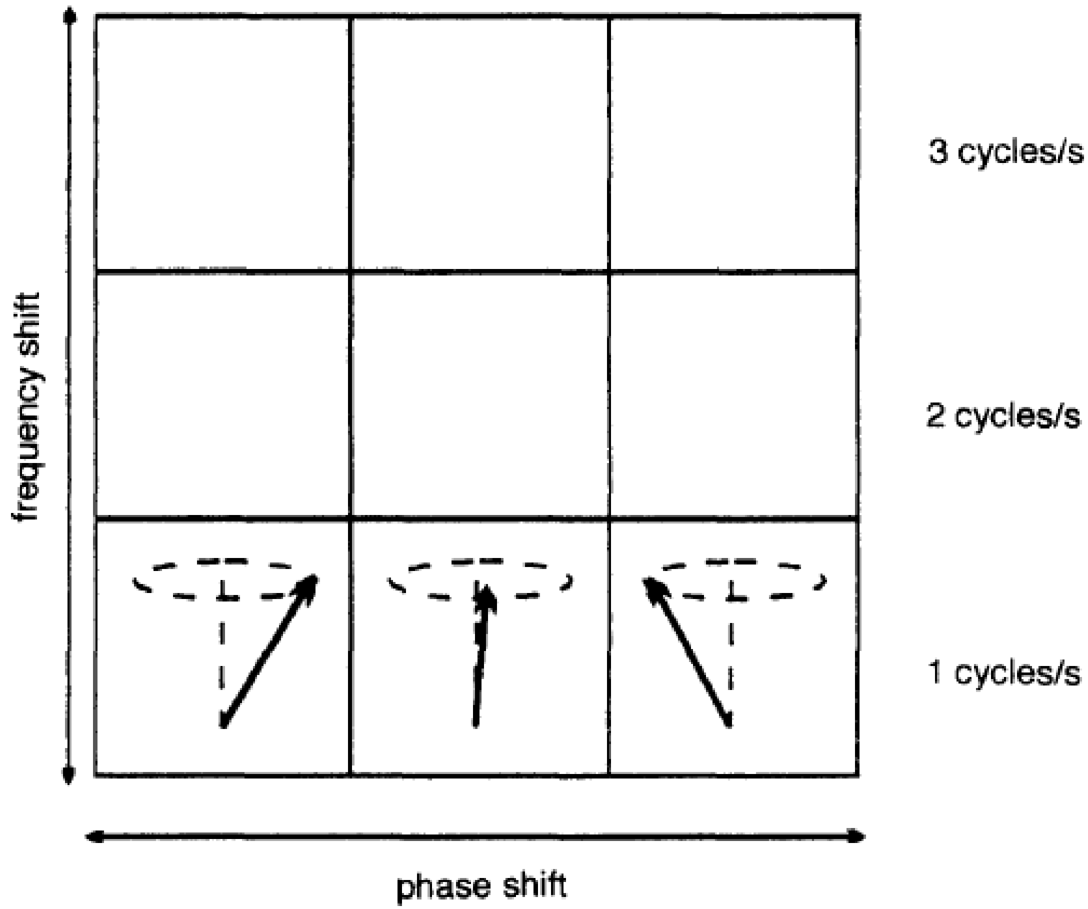




Summary


TR
180°
90°
echo
90°
slice
select
phase
encode
slice
select
frequency
encode


Phase
Slice
Selection
Readout


frequency shift
3 cycles/s
2 cycles/s
1 cycles/s
phase shift

K space

a) Definition:

- Area to store image data information until the scan is over
- Considered as spatial frequency domain, i.e. information about the frequency of a signal and where it comes from in the patient is stored.

b) Composition:

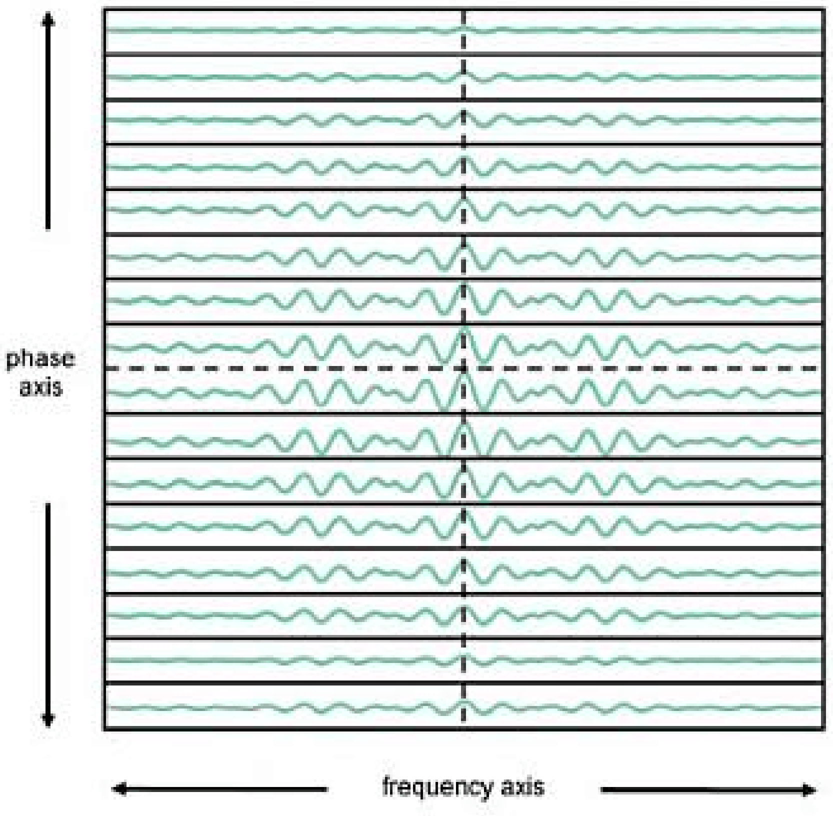
- Two axes:
  - **phase axis:** horizontal , centered in the middle of several horizontal lines.
  - **frequency axis:** vertical , centered in the middle of K space perpendicular to the phase axis

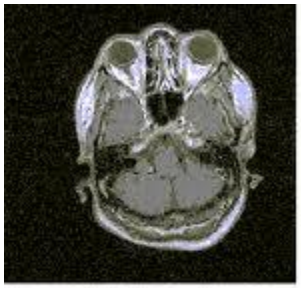
c) Note that:

- K space does not correspond to the image
- i.e. the top line of K space ≠ top line of the image
- It is later processed to produce an image

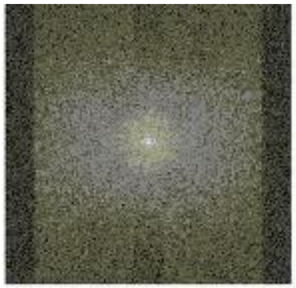
d) Unit:

- Radians per cm.





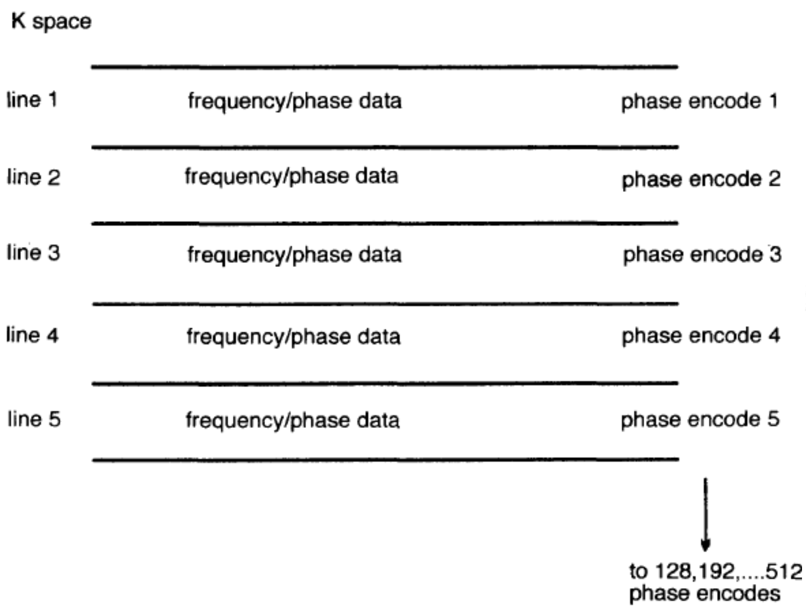
Spatial domain

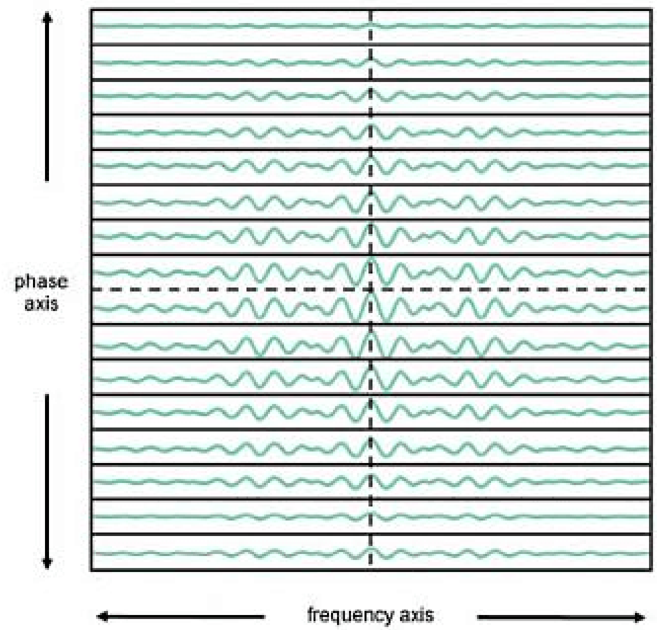


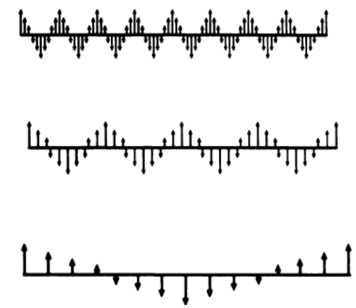
k space

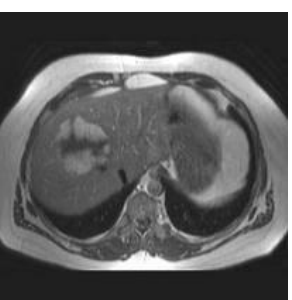
e) Steps of K-space filling:

1. During TR The slope of the phase encoding gradient ,will determine which line of K space is filled with the data
2. In order to fill out different lines of K space, the slope of the phase encoding gradient must be altered after each TR (If not→ the same line of K space is filled in all the time).
3. In order to finish the scan *all the* selected lines of K space must be filled (determined by the number of different phase encoding slopes)
4. Frequency shift determines FOV which remains unchanged during the scan→ the steepness of frequency encoding gradient is unchanged with every TR

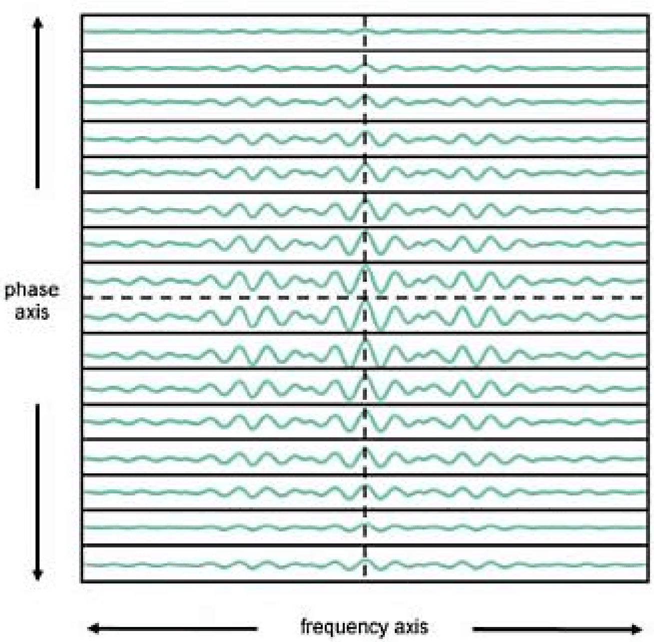


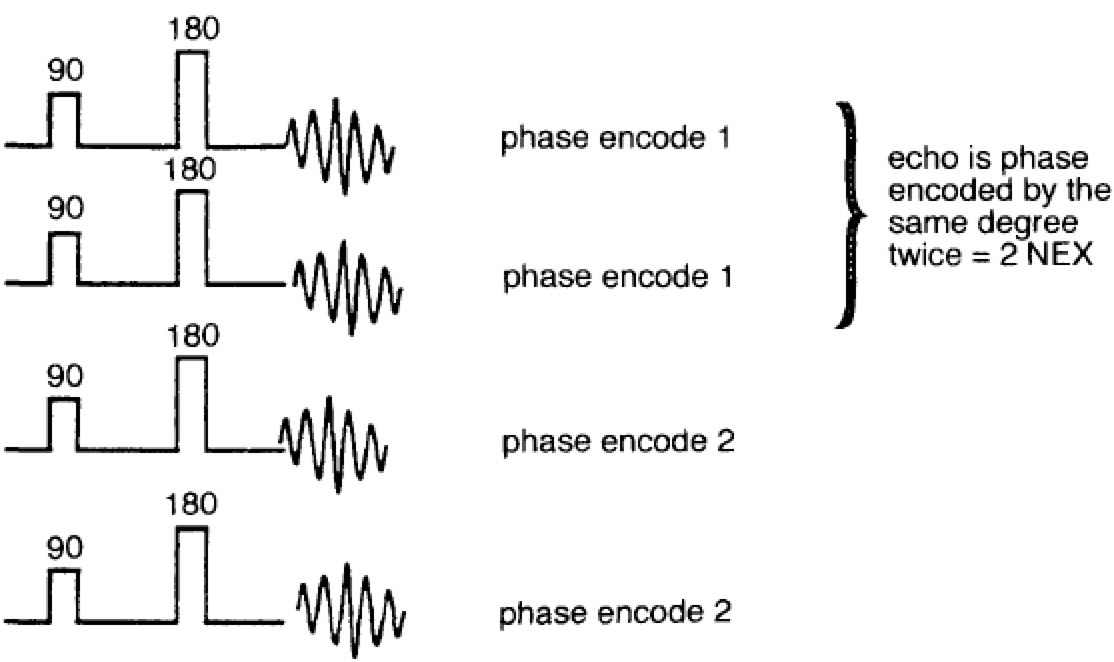






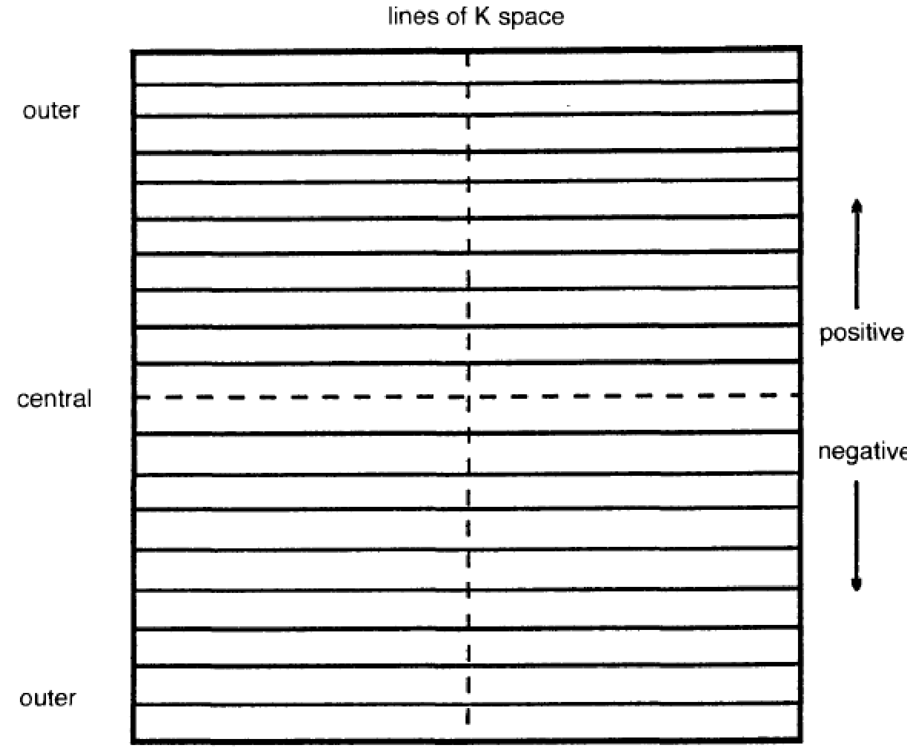
5. When all the lines of K space are filled, The signal can be sampled more than once with the same slope of phase encoding gradient (i.e. each line of K space is filled more than once)
   - ***Number of signal averages (NSA)= number of excitations (NEX) :***
     - The number of times each signal is sampled with the same slope of phase encoding gradient
   - The higher the NEX→ more data is stored in each line of K space. → more amplitude of signal





f) K space lines

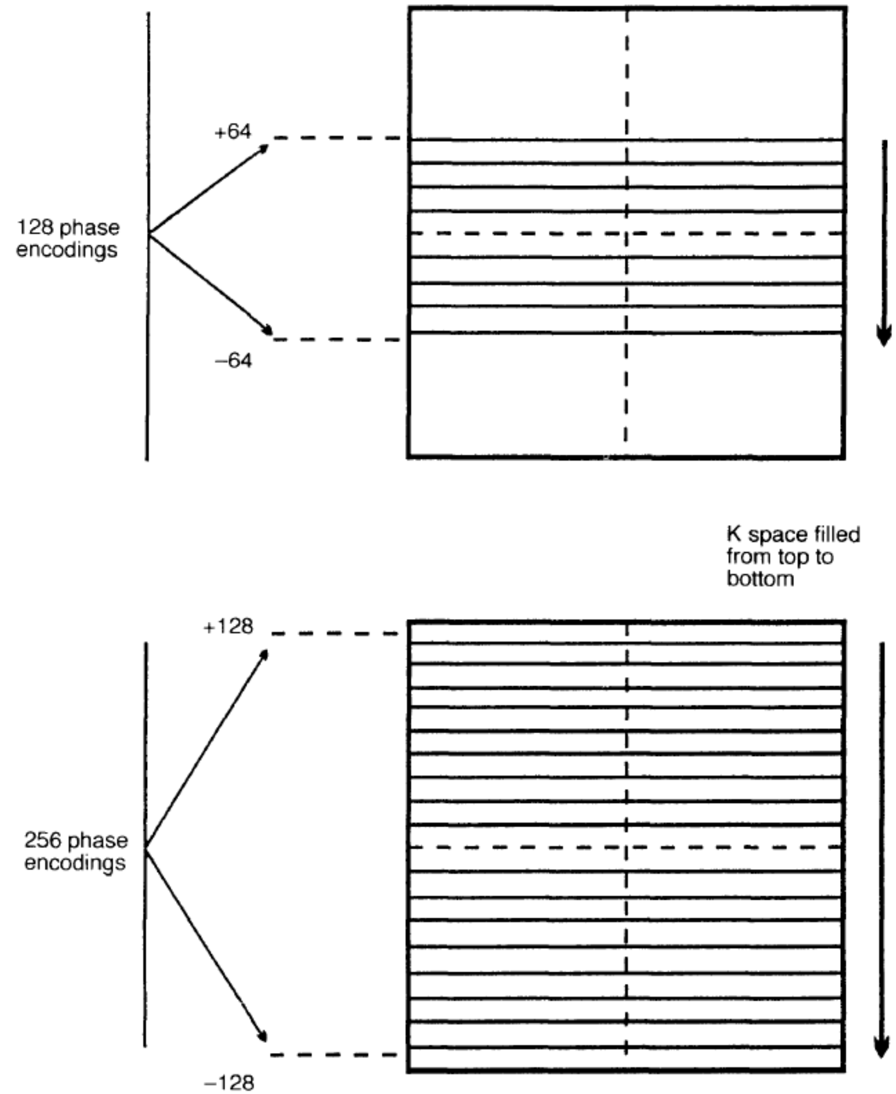
- ***Positive lines:***
  - The lines of K space above the phase axis.
  - *Filled with data* produced after the application of +ve phase encoding gradient.
- ***Negative lines:***
  - The lines of K space below the phase axis.
  - *Filled with data* produced after the application of -ve phase encoding gradient.
- ***Central lines:***
  - The lines nearest to the phase axis both positively and negatively
  - *Filled with data* produced after the application of shallow phase encoding gradient slopes.
- ***Outer lines:***
  - The lines farthest away from the phase axis both positively and negatively
  - *Filled with data* after the application of the steep phase encoding gradient
- The negative half of K space is a mirror image of the positive half of K space,



g) Important notes about k-space:

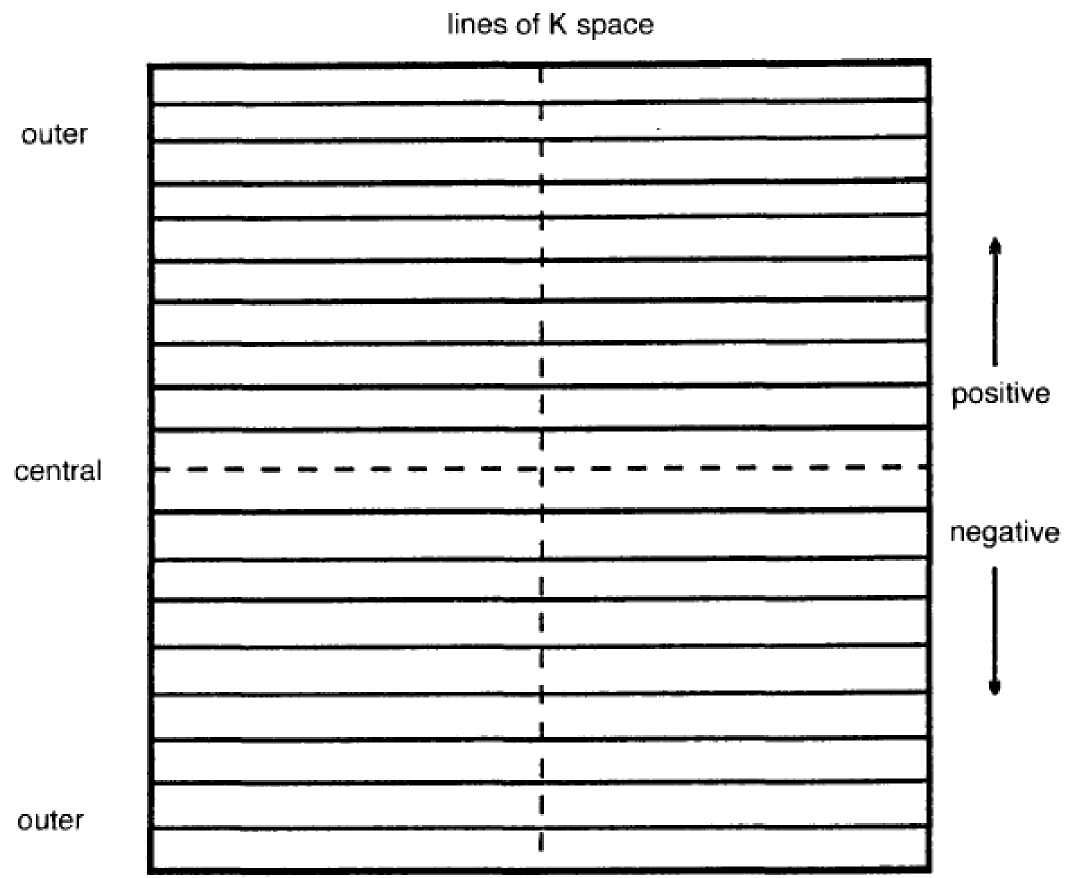
1- The central lines of K space are usually filled first

- If 128 phase encodings are performed, the central 128 lines are filled (64 positive, 64 negative).
- if 256 phase encodings are performed 128 positive and 128 negative lines of K space are filled.



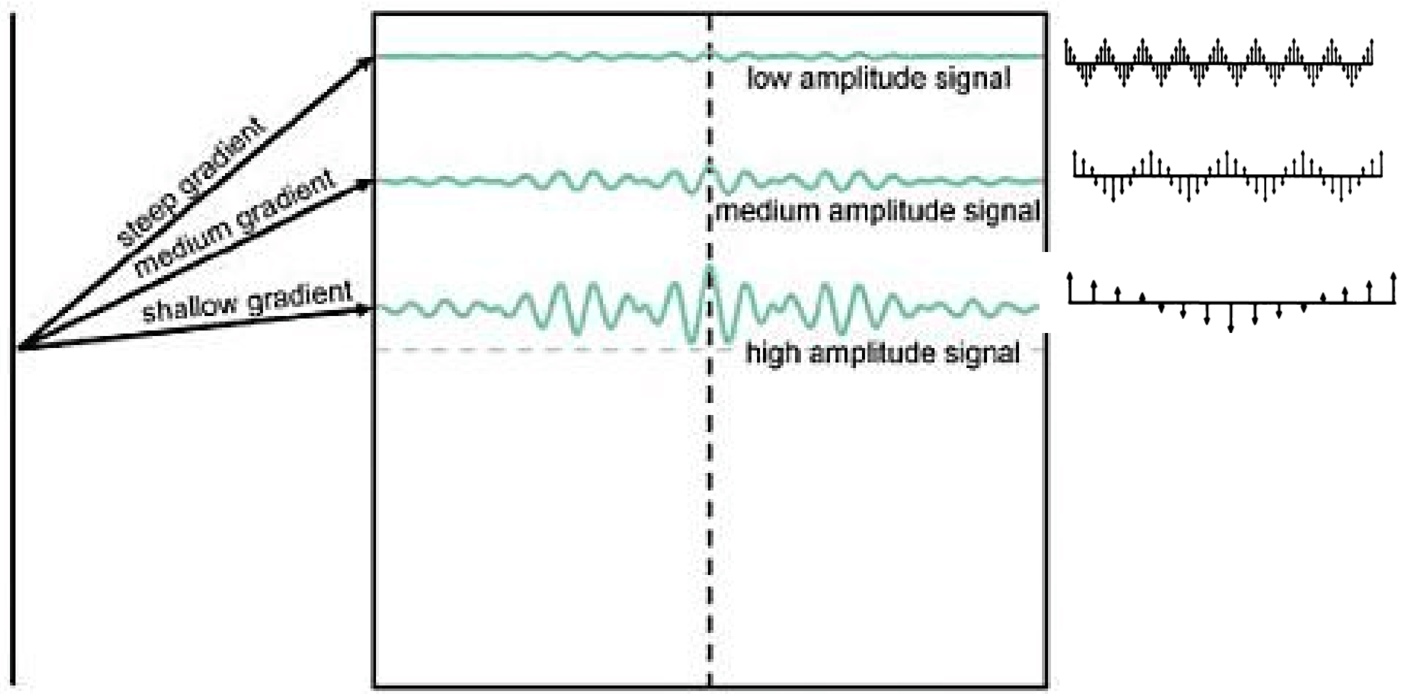
2- K space lines are usually filled sequentially:

- From top to bottom
- Or from bottom to top.
- Can also be filled from the centre out or from the edges in.



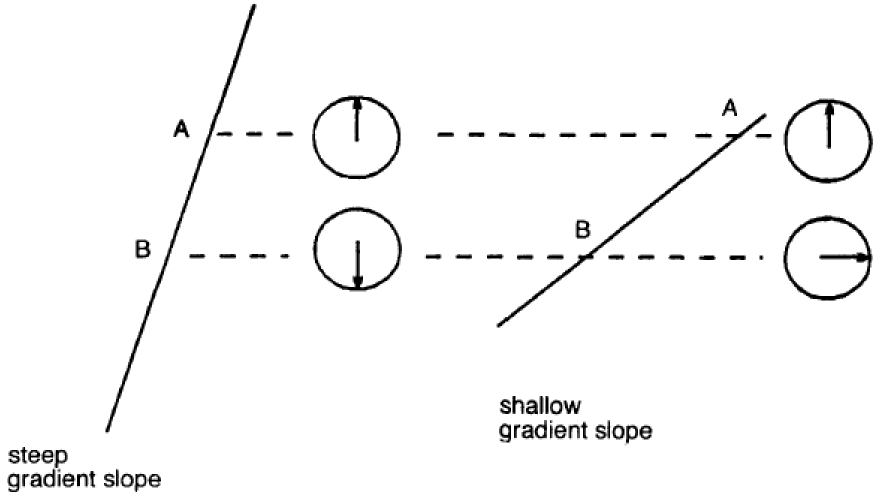
3- K-space lines and signal amplitude

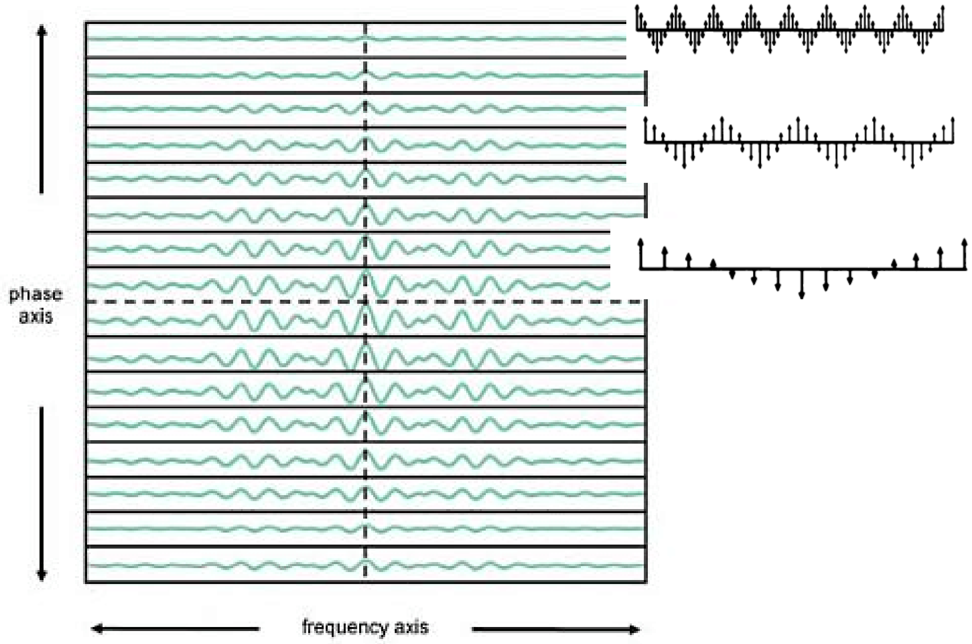
- Shallow phase encoding slopes do not produce a large phase shift along their axis. The resultant signal has a large amplitude.
- Steep phase encoding slopes produce a large phase shift along their axis. The resultant signal has a small amplitude



4- K-space lines and spatial resolution

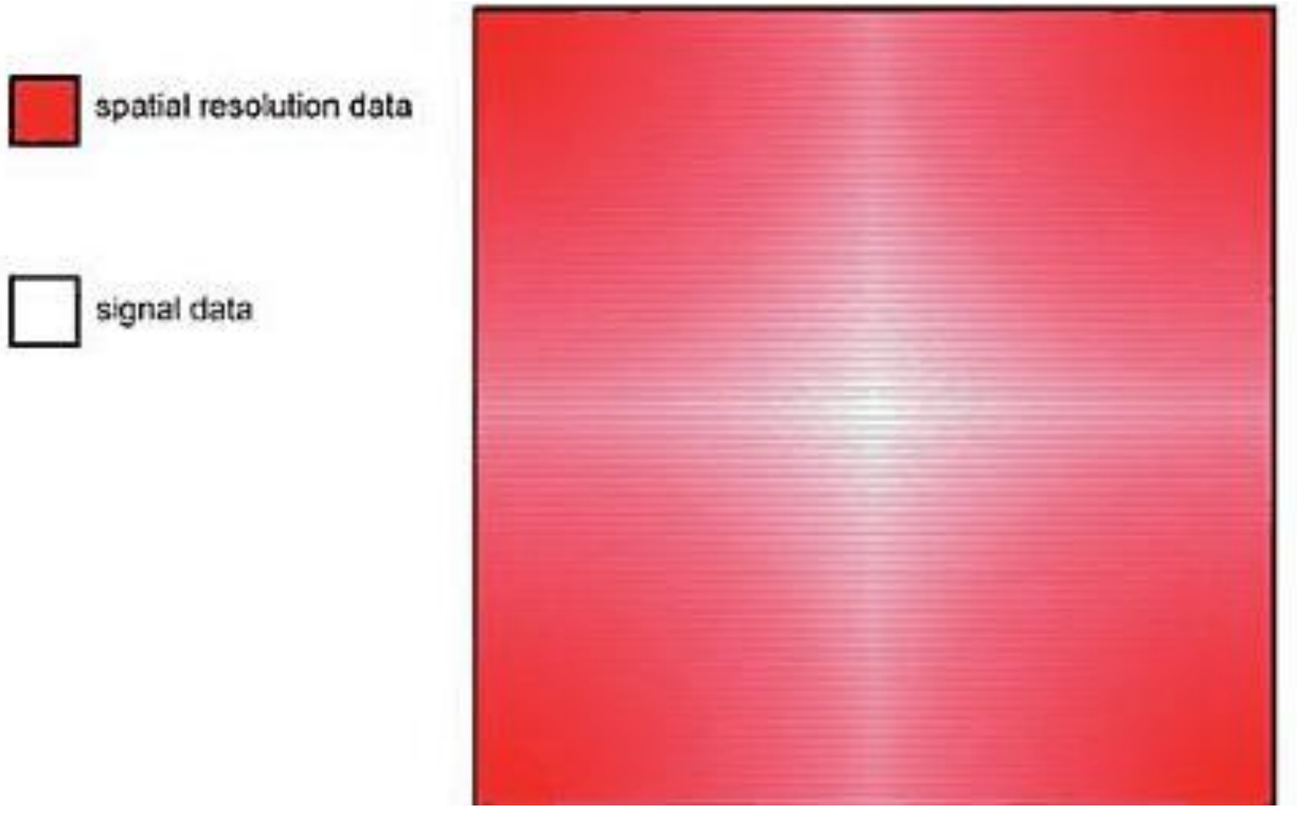
- ↑slope of the phase encoding gradient → degree of phase shift along the gradient also ↑ → Two points adjacent to each other have a highly different phase value → can therefore be differentiated from each other.
- i.e. Data collected after steep phase encoding gradient slopes produces greater spatial resolution in the image.

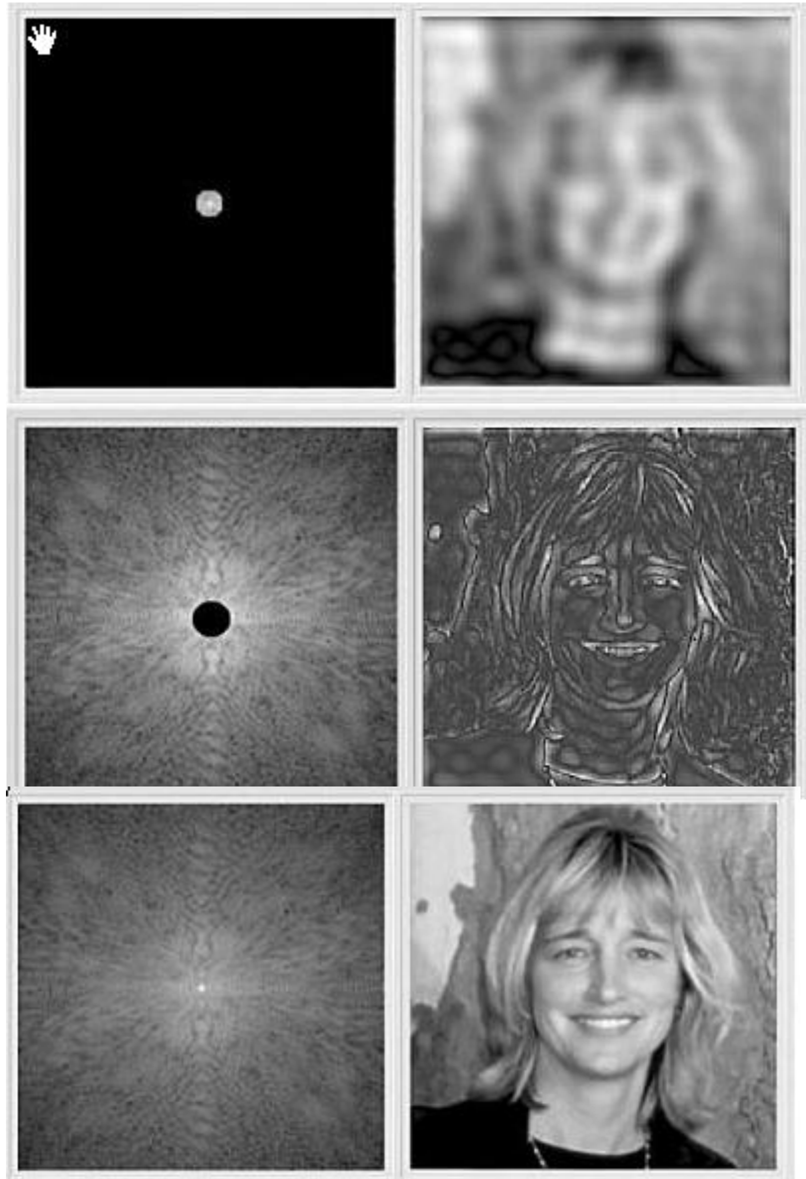




Result:

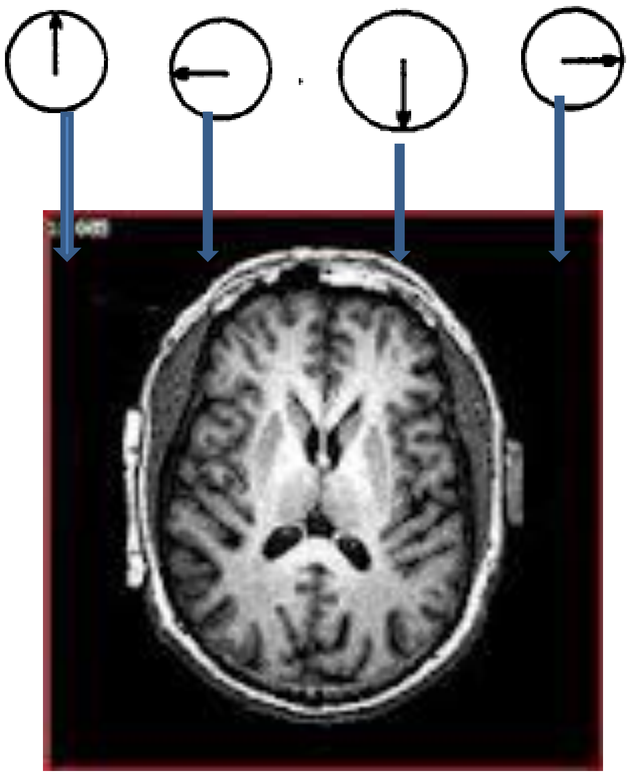
- The central portion of K space contains data that has high signal amplitude and low spatial resolution.
- The outer portion of K space contains data that has high spatial resolution and low signal amplitude

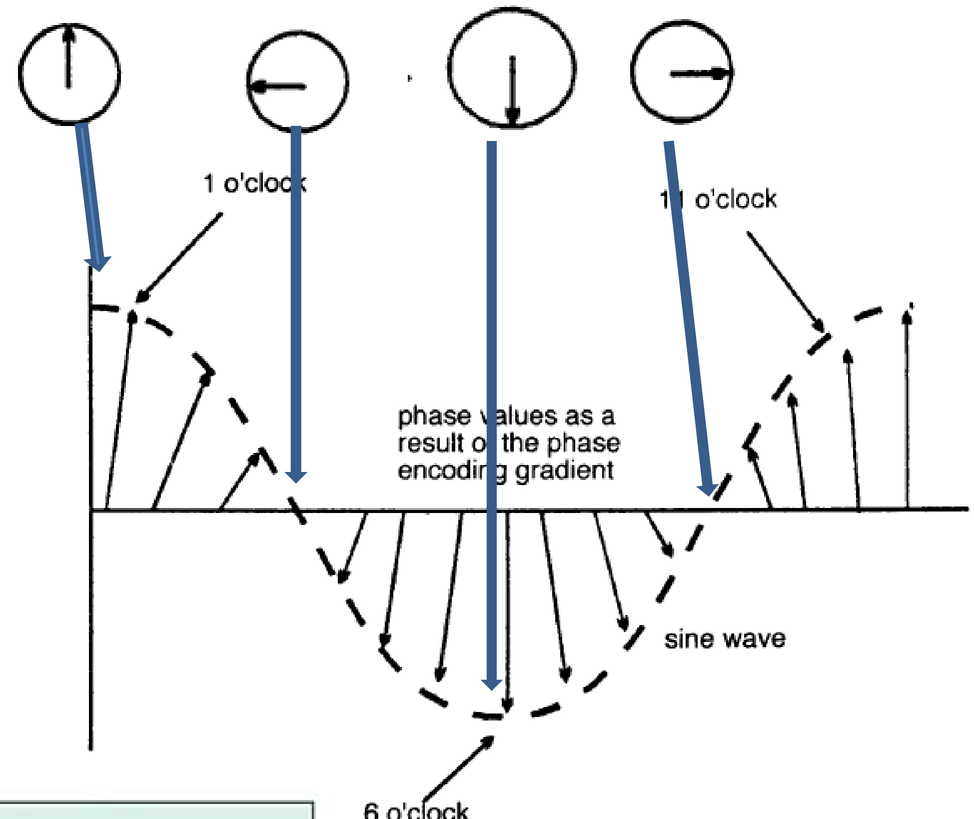


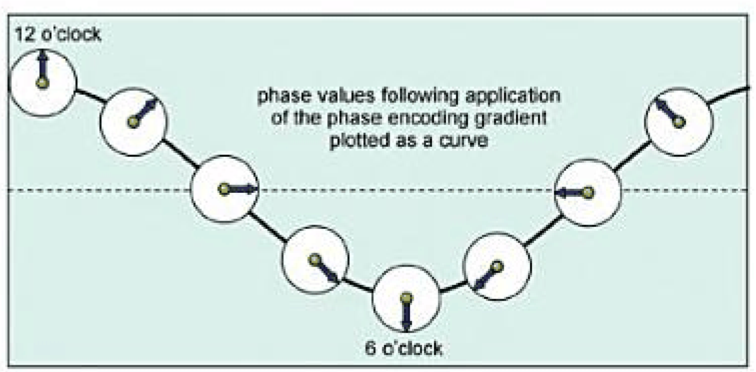


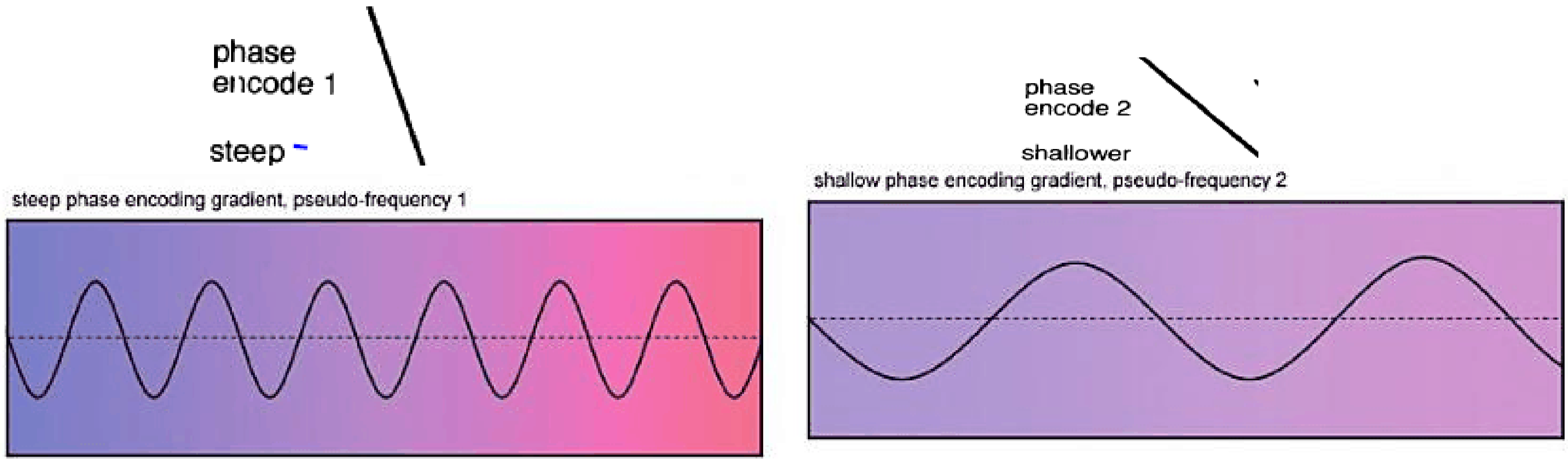
5- Method of determining which line is going to be filled in the k-space:

- phase shift values are converted into frequencies by creating a sine wave formed from connecting all the phase values associated with a certain phase shift
- This sine wave has a certain frequency (*pseudofrequency) , determine the phase shift and k line filled*



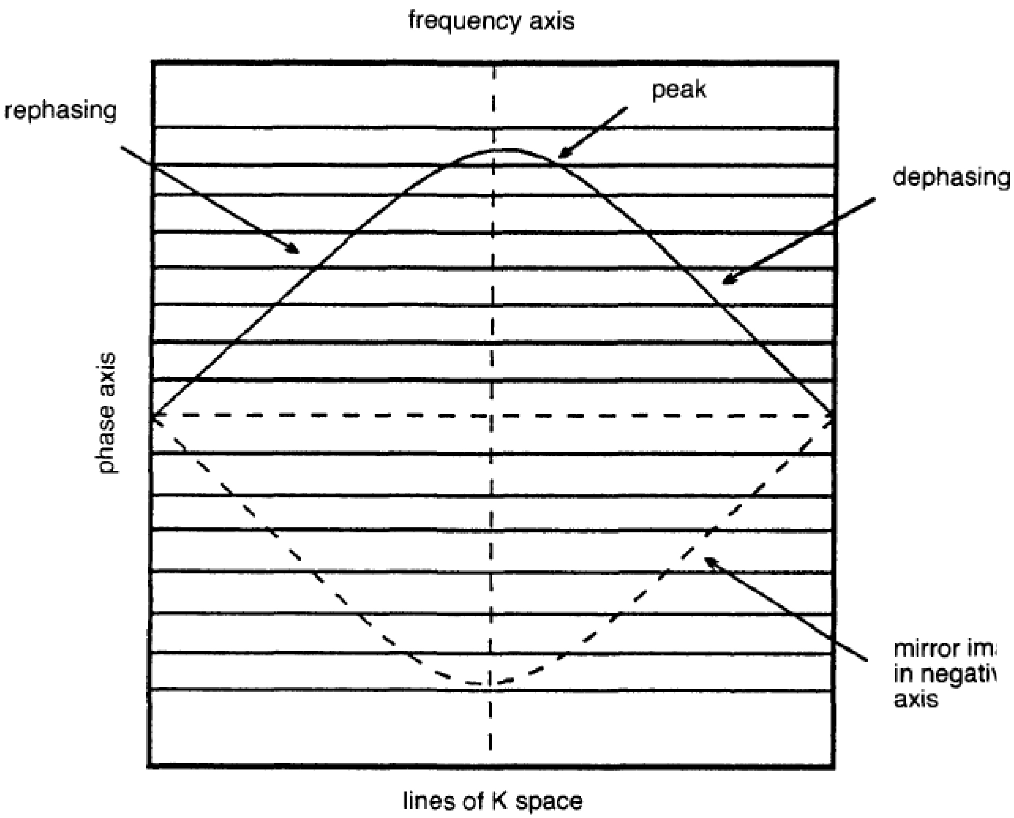


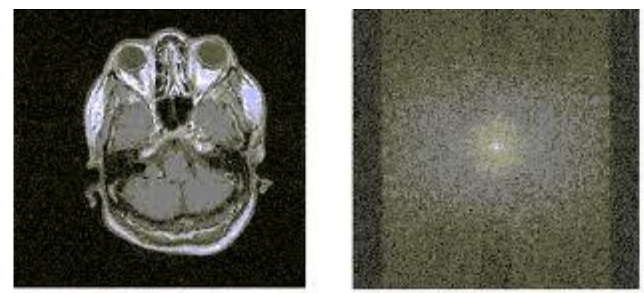



phase
encode 1
steep
steep phase encoding gradient, pseudo-frequency 1
phase
encode 2
shallower
shallow phase encoding gradient, pseudo-frequency 2

6- The vertical axis of K space:

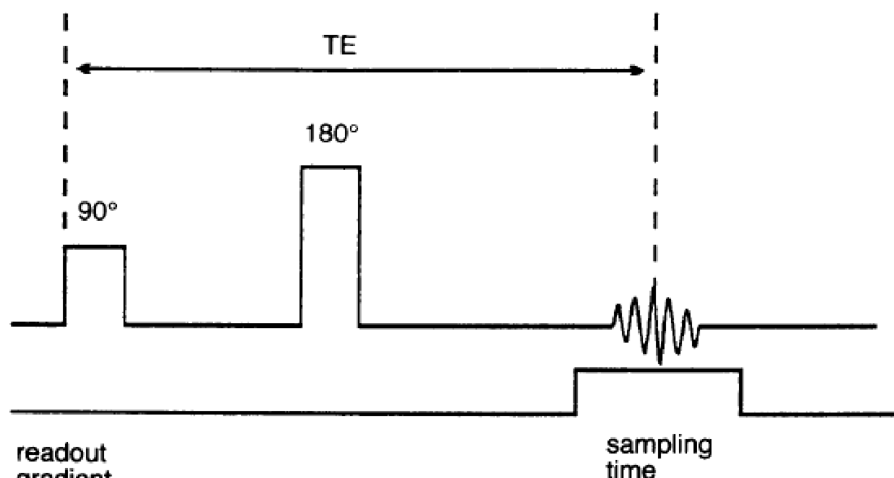
- Corresponds to the frequency encoding axis.
- The area of K space to the left of the frequency axis is a mirror image of the area to the right of the frequency axis.
- The centre of the echo represents the maximum signal amplitude (all the magnetic moments are in phase) ,
- the magnetic moments are either rephasing or dephasing on each side of the peak of the echo, (signal amplitude is less).





Spatial domain

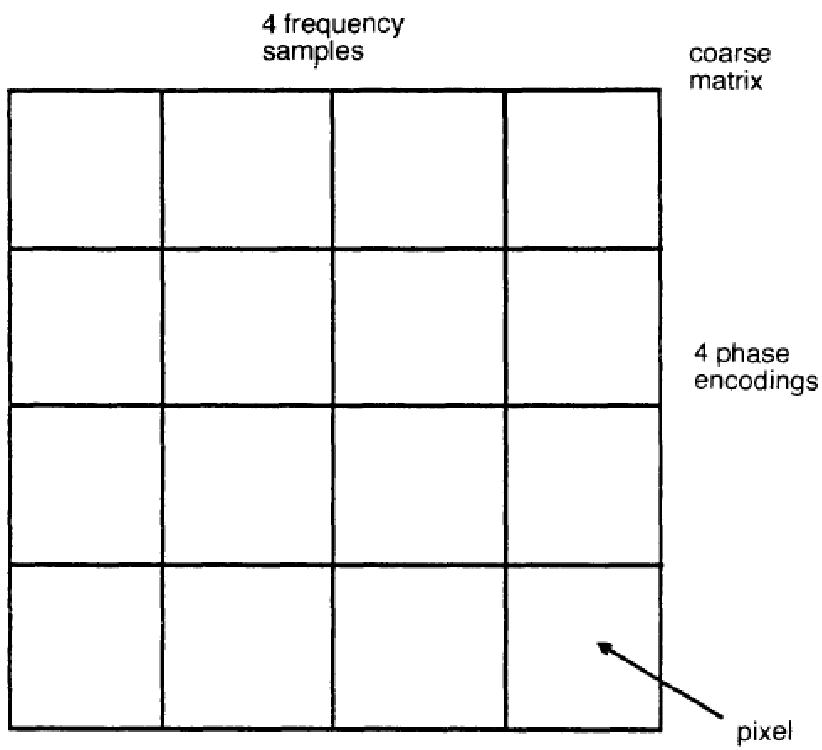
k space

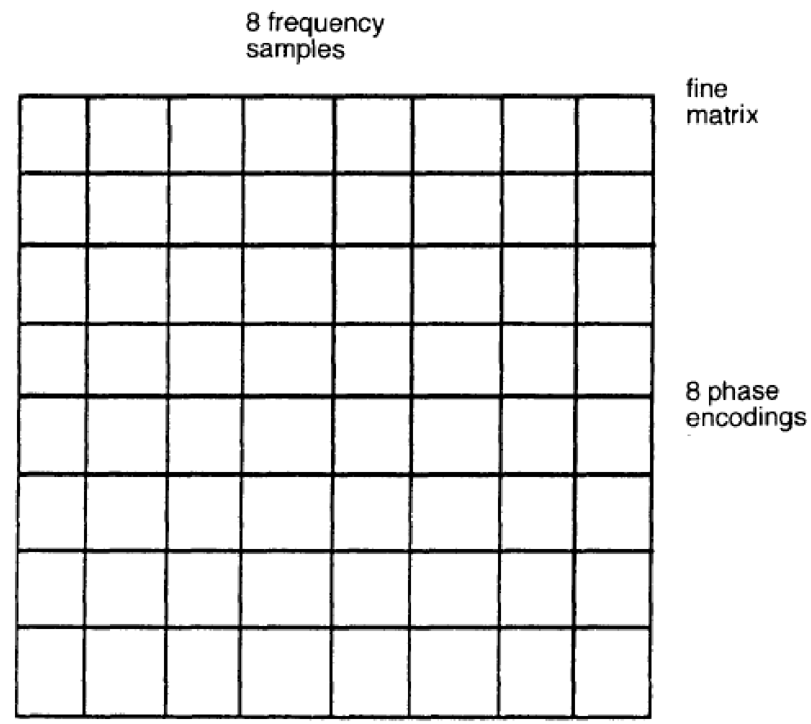


7- Image matrix:

- The FOV is divided up into pixels
- The number of pixels within the FOV depends on the number of frequency samples and phase encodings performed.

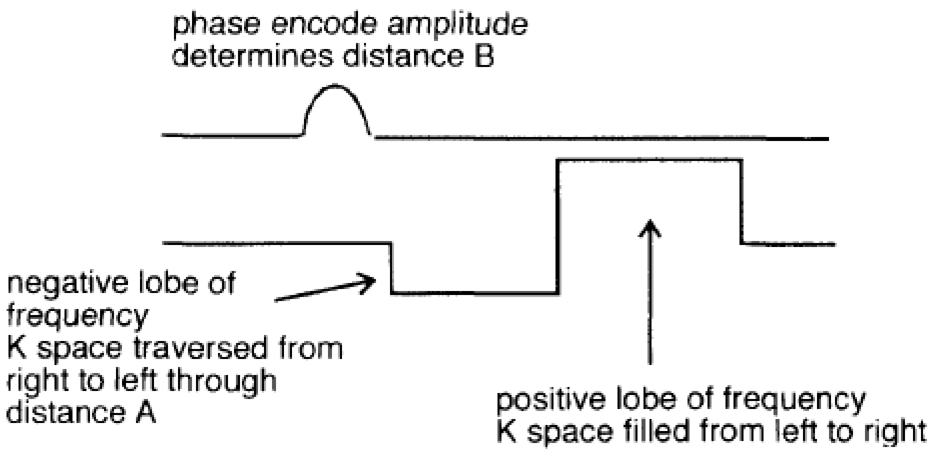
e.g. 256 x 192 indicates that 256 frequency samples are taken during readout and 192 phase encodings are performed.

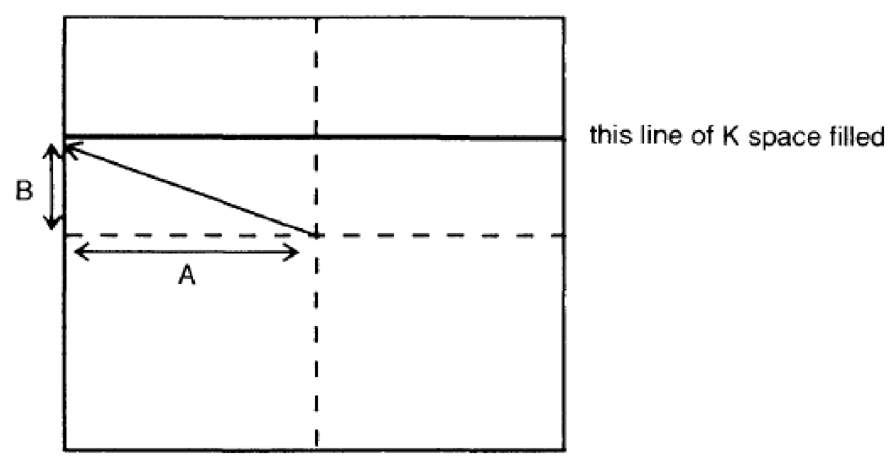




8- K space filling in gradient echo pulse :

- In a gradient echo sequence the frequency encoding gradient switches negatively to forcibly dephase the FID and then positively to rephase and produce a gradient echo
- When frequency encoding gradient is negative, K space is traversed from the centre to the left, to a distance (A) which depends on amplitude of –ve lobe of frequency encoding gradient.
- The amplitude of phase encoding gradient determines the distance travelled (B).
- The frequency encoding gradient is then switched positively and data is placed in a line of K space from left to right.





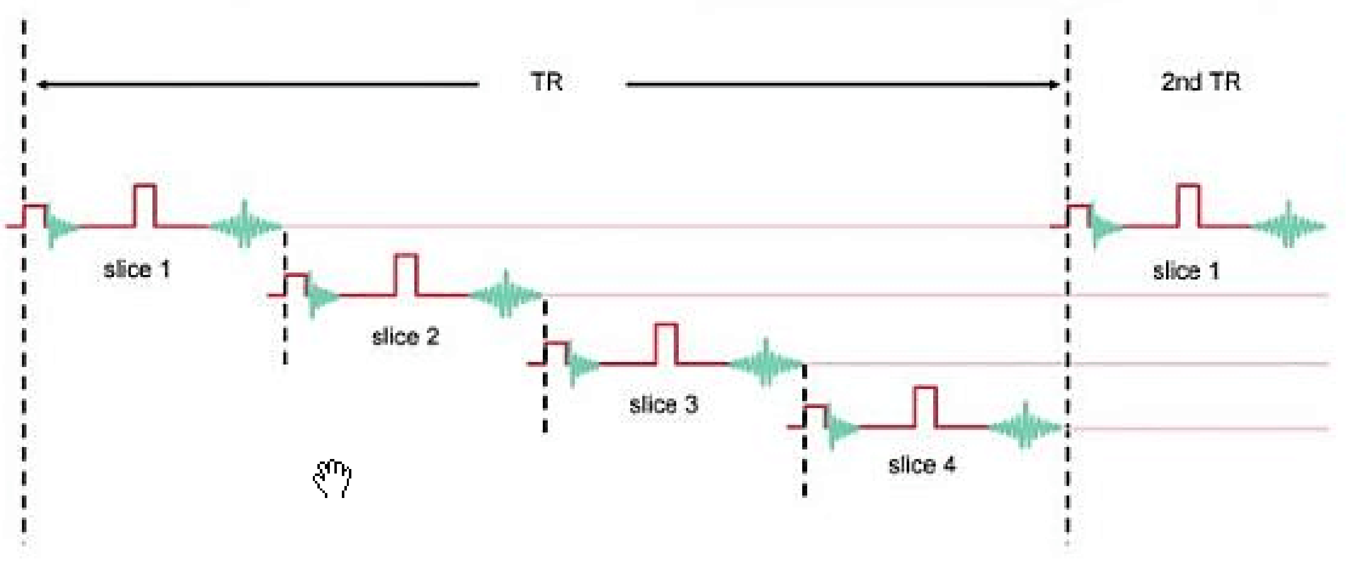
Scan timing:

Scan time = TR x number of phase encodings x NEX

- The phase encoding gradient slope is altered with every TR → number of phase encoding steps affects the length of the scan.
  - 128 phase encodings requires 128 x TR to complete the scan.
  - 256 phase encodings requires 256 x TR to complete the scan.
- The scan time is also affected by NEX.

Important note

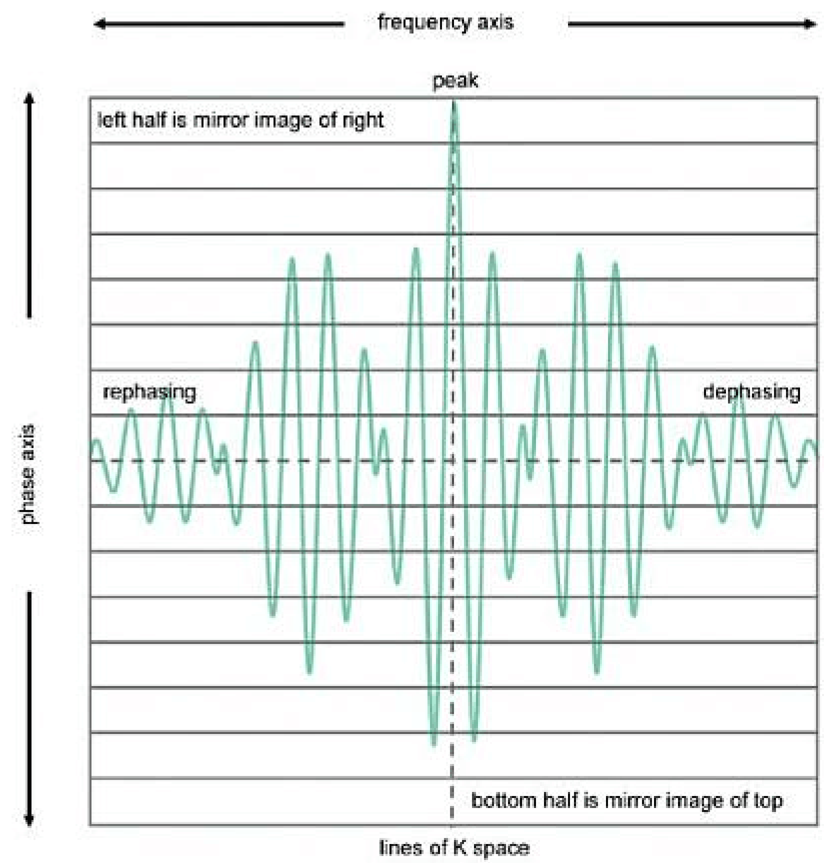
- Multiple slices are scanned in the same TR
- Explanation:
  - Same phase encoding step of all slices are performed in the same TR before changing the phase encoding slope in the next TR)
- The maximum number of slices that can be selected and encoded depends on the length of the TR:
  - Longer TR → more slices to be selected and encoded



Partial or fractional echo imaging

Definition:

- Only part of the signal is read during application of the frequency encoding gradient filling only part area of K space along the frequency axis.
- The remaining is a mirror image → the system can calculate its amplitude.

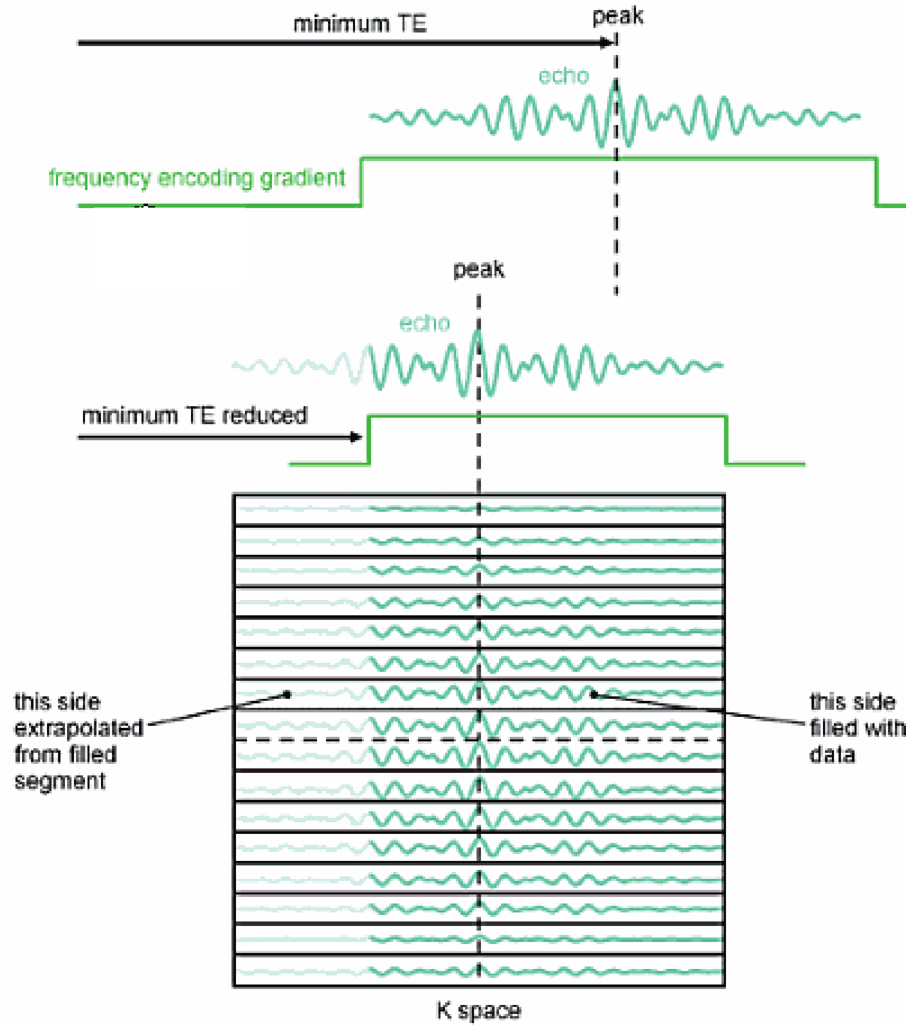


Advantage:

- TE can be reduced (usually partial echo imaging is used when a TE of less than 20 ms is selected) → Allows for maximum T1 and slice number for a given TR

Explanation:

- The echo no longer has to be centered on the middle of the frequency encoding gradient.
- Only the peak and the dephasing part of the echo are sampled→ peak of the echo can occur closer to the RF excitation pulse.



Partial or fractional averaging

Definition:

- 60% of K space lines is filled by performing only 60% of the phase encodings
- the remaining lines are filled with zeros.

Example:

- if 256 phase encodings, 1 NEX and TR of 1 s are selected →normally Scan time= 256 x 1 x 1 = 256 s
- If NEX= ¾ (Only 75% of K space is filled) → Scan time= 256 x 3/4 x 1= 192 s

Adv.:

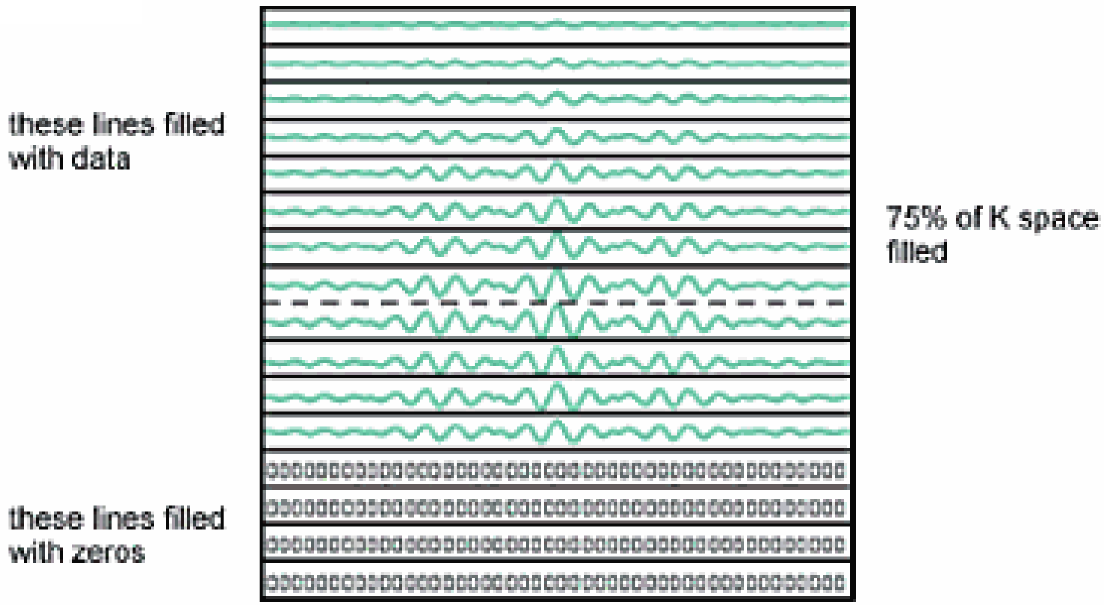
- The scan time is reduced

Disadvantage:

- less data is acquired so the image has less signal.

Uses:

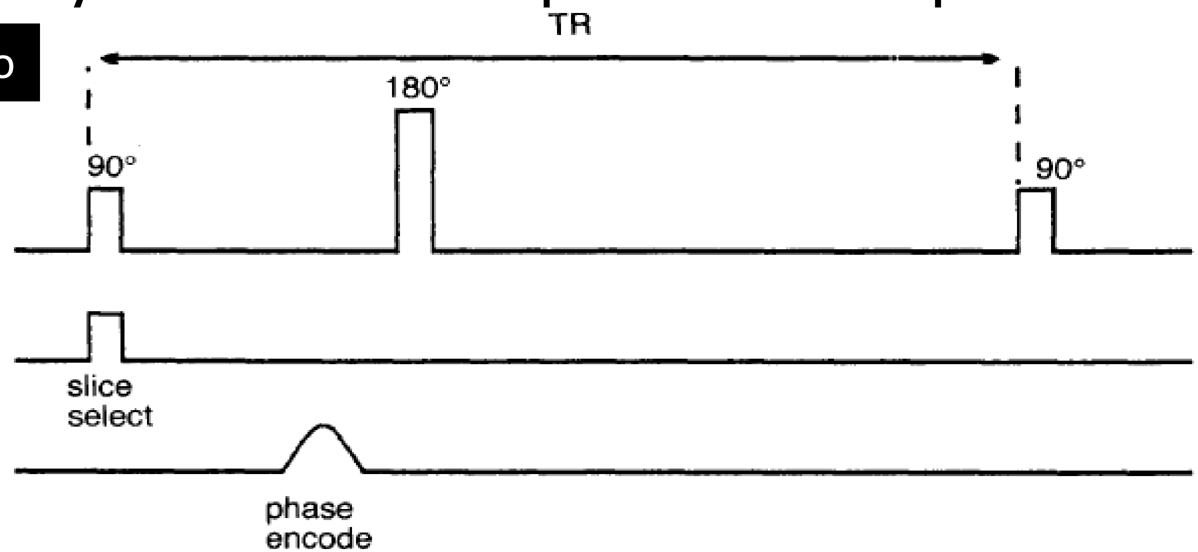
- Used when a reduction in scan time is necessary, and the resultant signal loss is not of paramount importance.

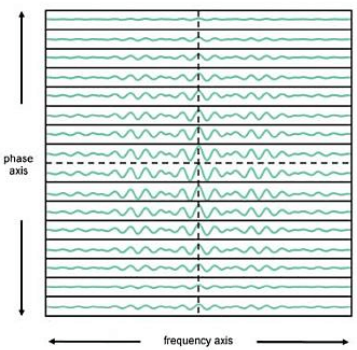


Fast spin echo pulse sequence

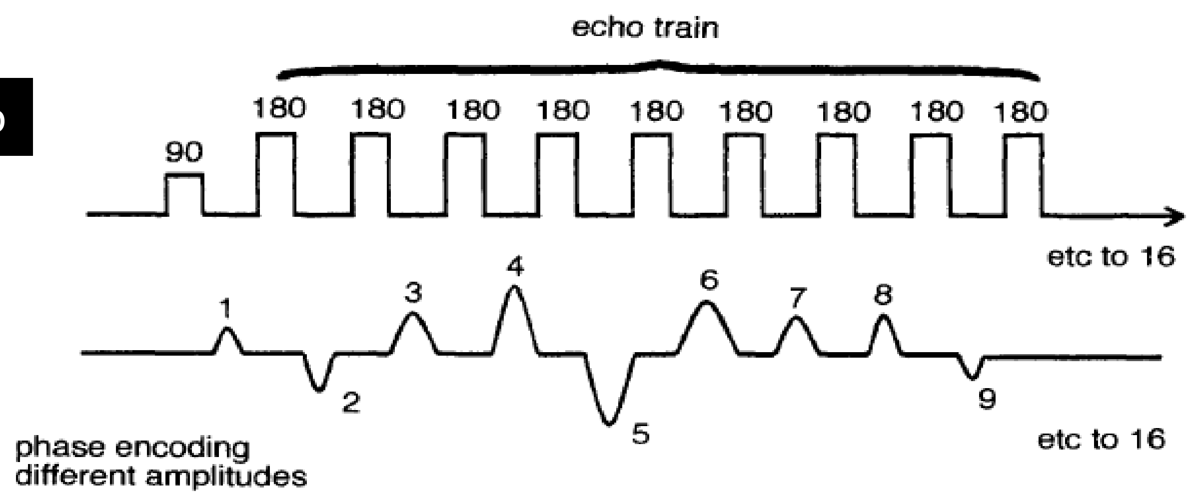
- *Idea of fast spin echo:*
  - Same as spin echo pulse sequence, but more than one phase encoding step is performed per TR
    i.e. more than only one line of K space is filled per TR

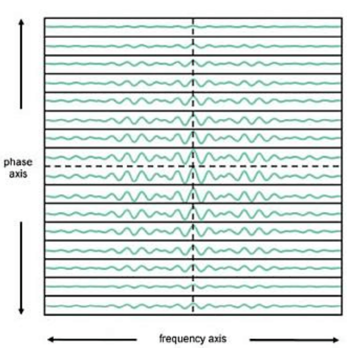
Conventional spin echo



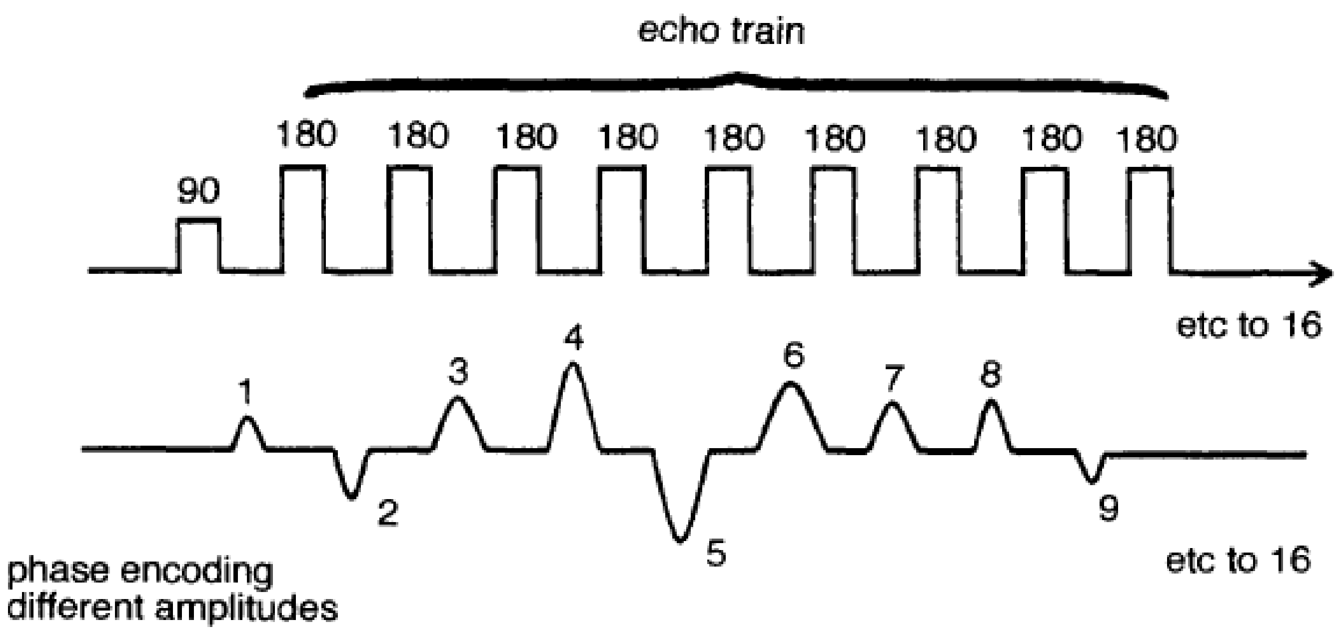


Fast spin echo





– In other words:
- Echo train is used consisting of several 180^o rephasing pulses, each of them an echo.
- A different phase encoding step is performed with every 180 ^{o} pulse
- Data from different echoes in the same TR is placed into one slice.



- ***Turbo factor or the echo train length:***
  - The number of lines of K space filled (phase encoding steps performed) per TR

  = The number of 180^o rephasing pulses performed per TR

  - *The higher the turbo factor→the shorter* the scan time

<u>*Example:*</u>

•In conventional spin echo:

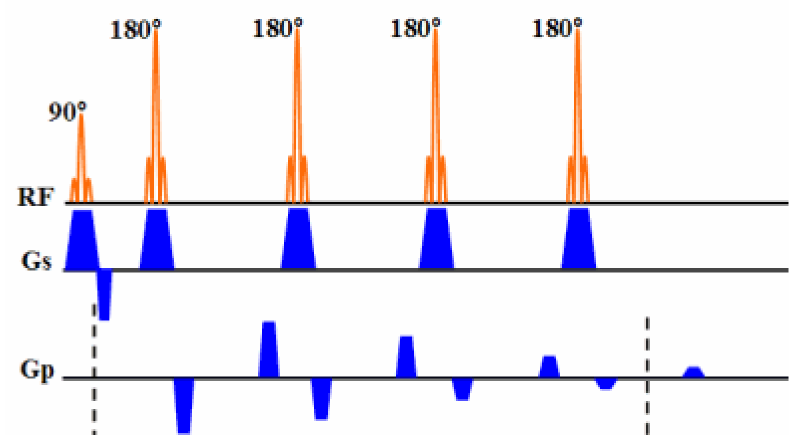
If 256 phase matrix selected

→256 phase encodings must be applied

→scan time = 256 x TR (if NEX=1) .

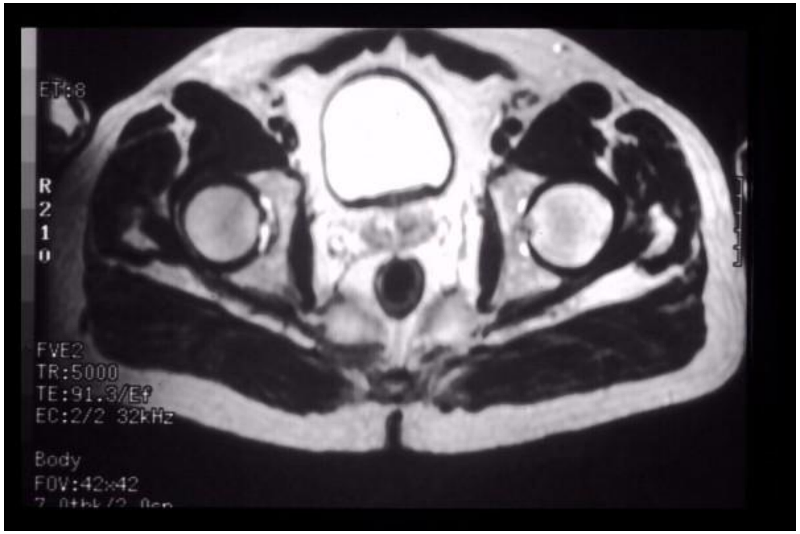
•In fast spin echo, using a turbo factor of 16 : scan time = 256/16 (16) x TR

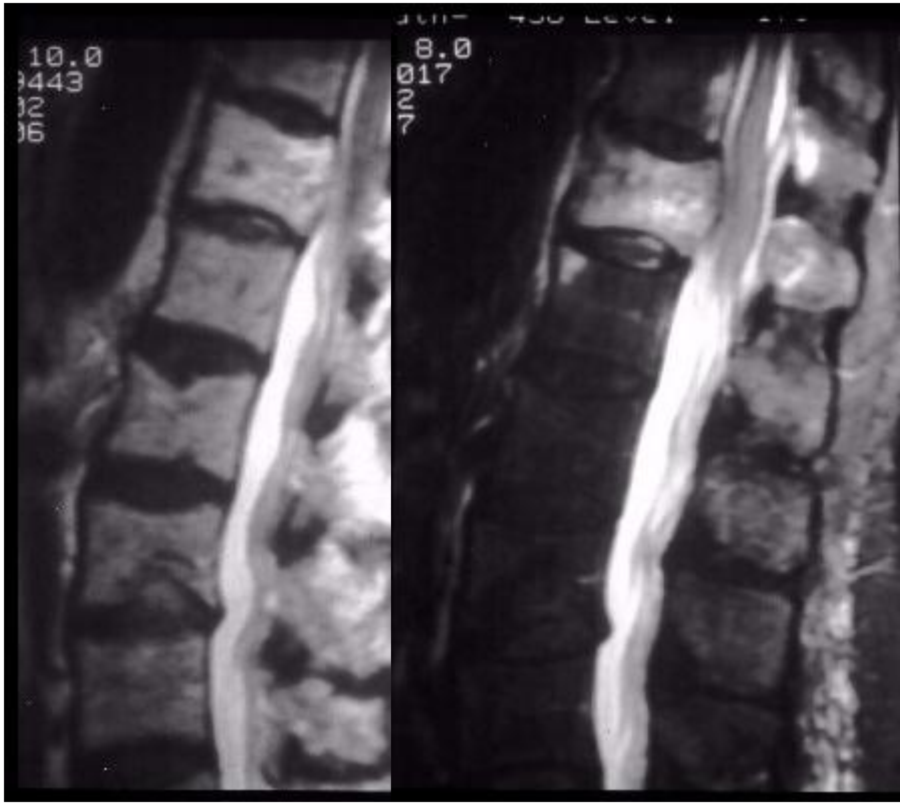
•i.e. The scan time is reduced to a 1/16th of the original.



Some results of repeated 180^{o} pulses of the echo train in Fast spin echo sequence :

1) Fat remains bright on T2 weighted images
   - Cause: due to reduction of the effects of spin-spin interactions in fat (J coupling)
   - Solution: fat saturation techniques





2) Magnetisation transfer effects increase → muscle appears darker than in conventional spin echo.

3) Magnetic susceptibility effects is reduced

   Hazard: can be detrimental when looking for small hemorrhages.

<u>*Image weighting in fast spin echo sequence:*</u>

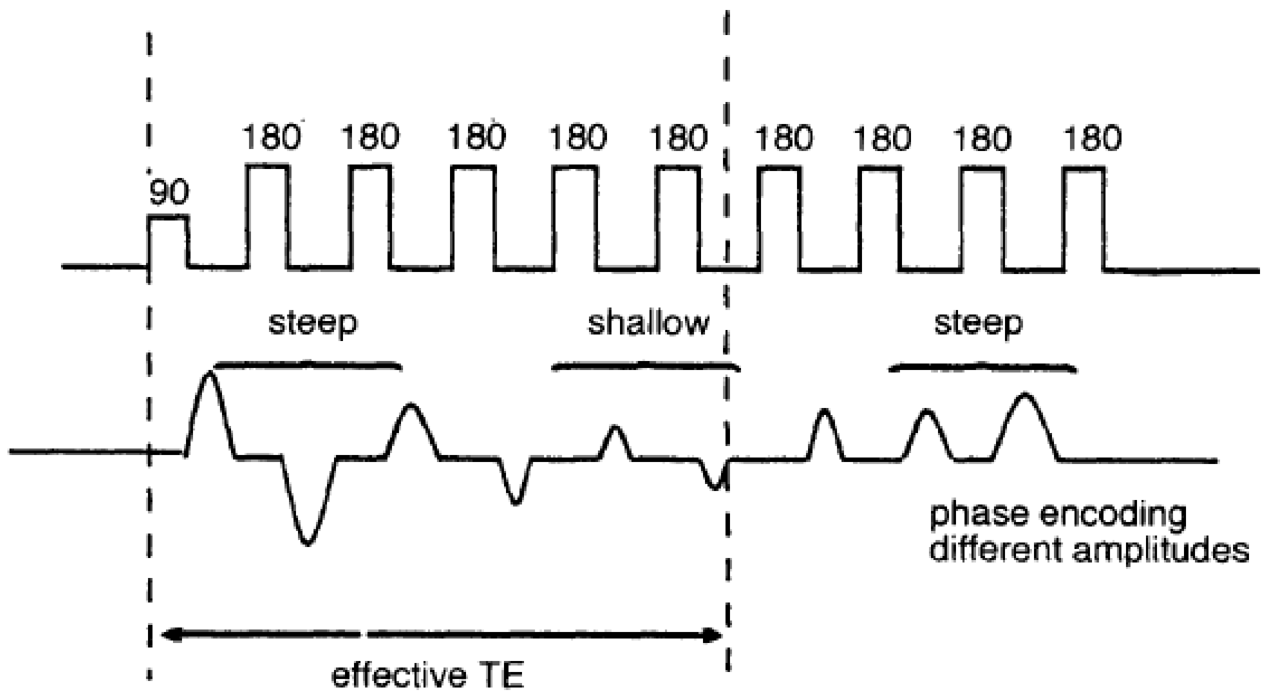
1) **<u>TE:</u>**

- ***Effective TE:***

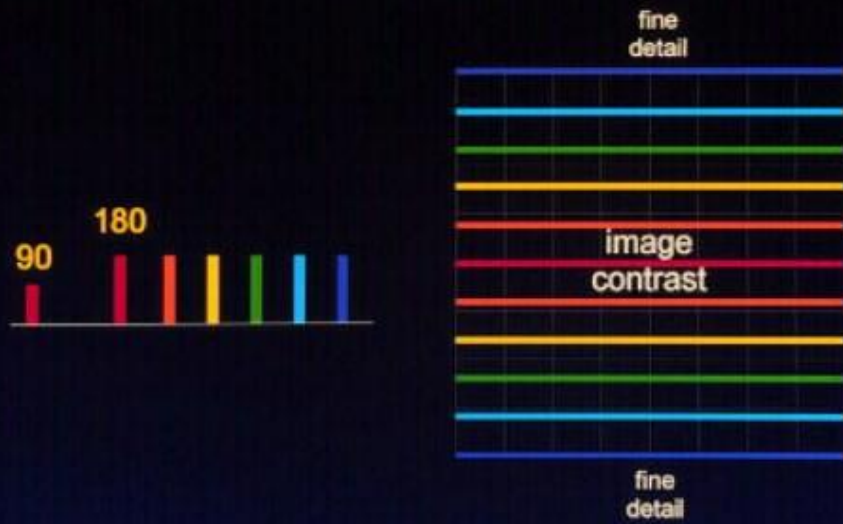
  TE at which the operator wishes to weight the resultant image.

- The system put the shallow phase encoding slopes that produce maximum signal centered on the effective TE selected.
- The steep slopes that produce a much smaller signal amplitude are placed away from the effective TE.

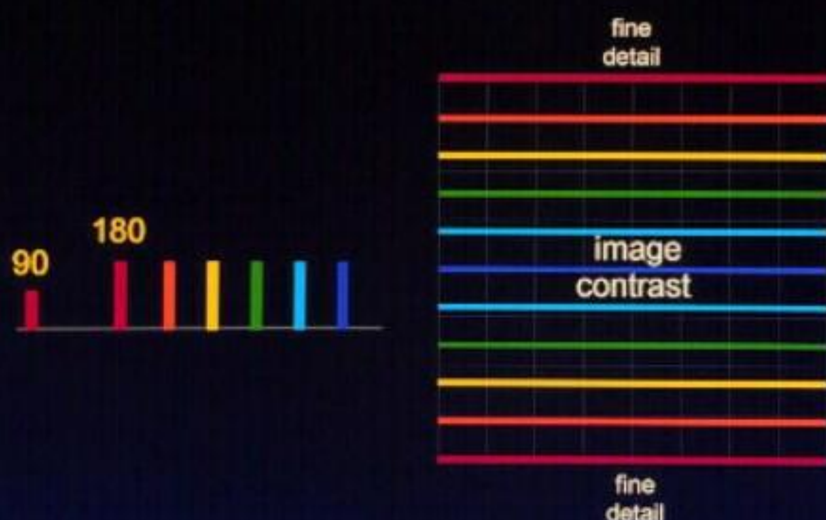
→data from echoes collected around the effective TE has more impact on image contrast as it fills the central lines of K space which produce the greatest signal amplitude.



PD-w FSE

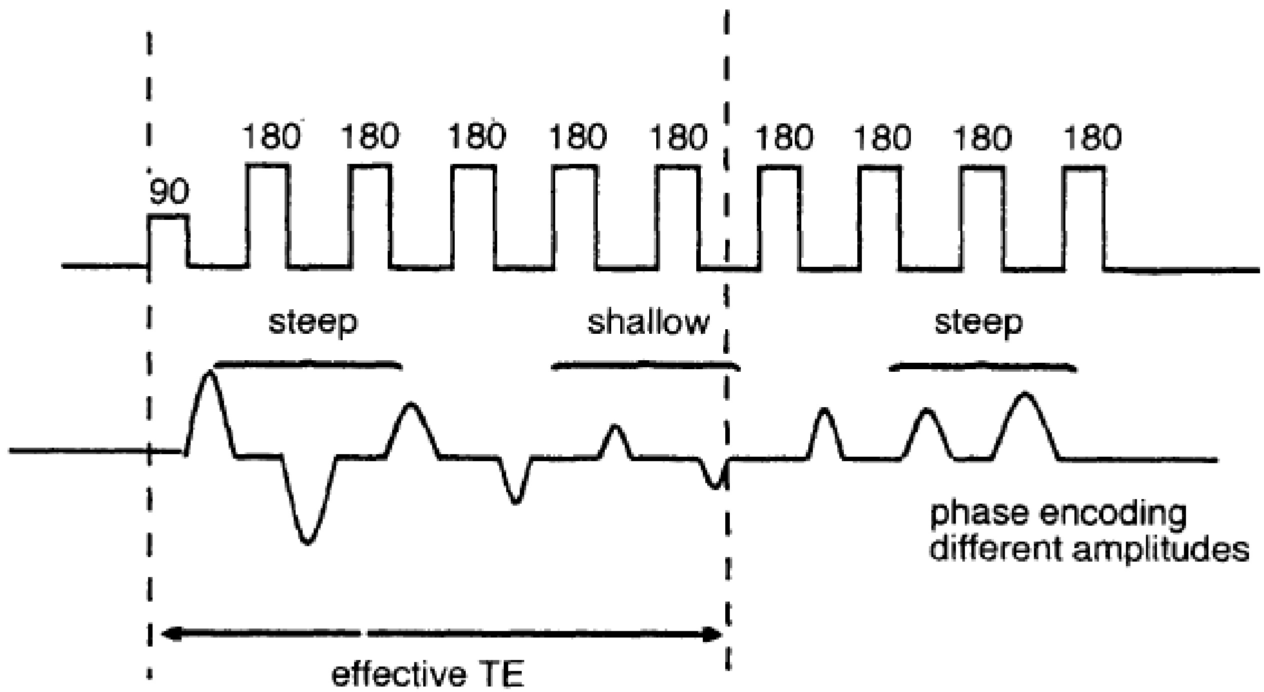


T2-w FSE



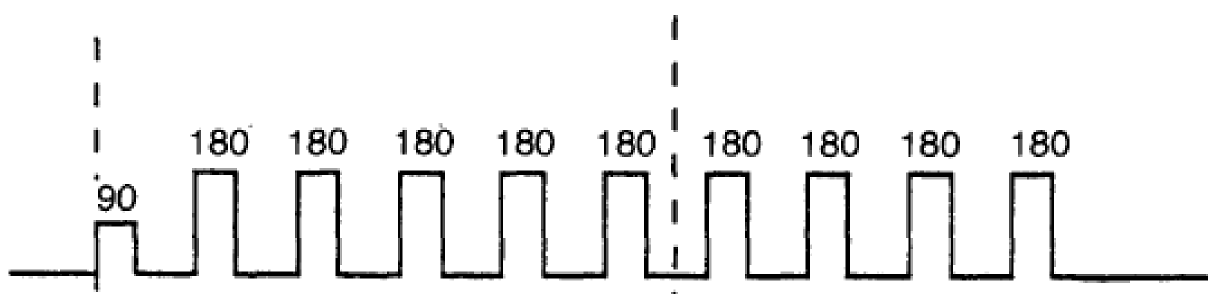
2) **TR:**

- TR of fast spin echo is often much longer than those used in conventional spin echo (The *180^o RF pulses take time to perform)*



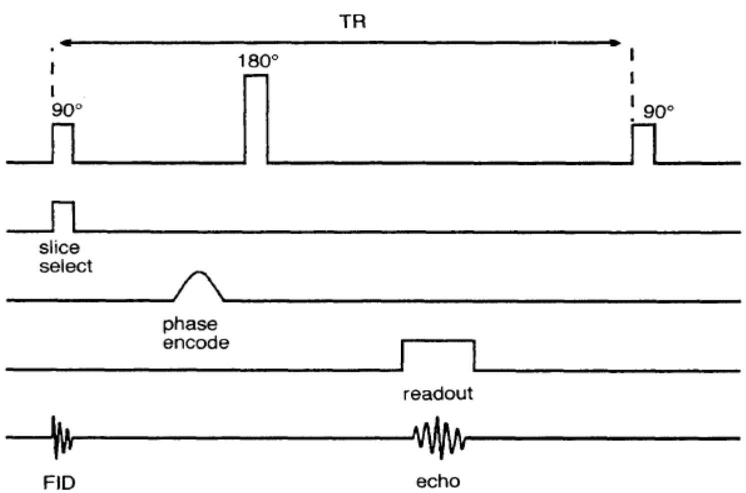
3) **<u>Turbo factor:</u>**

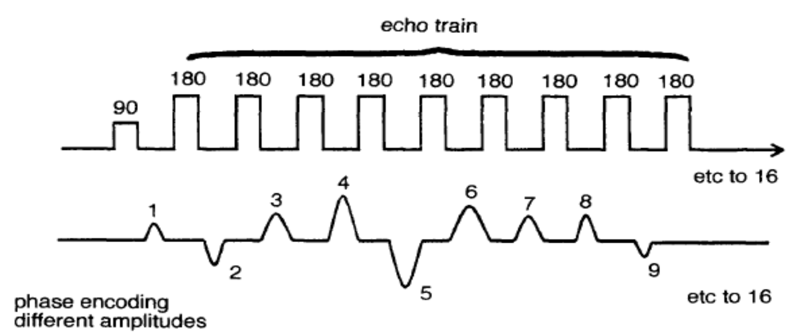
- The higher the turbo factor:
  - The shorter the scan time
  - The resultant image has more of a mixture of weighting because there is more data collected at the wrong TE
    - ❖ e.g. In T1 and PD weighting, larger turbo factors place too much T2 weighting in the image and cause blurring
    - ❖ →Image blurring occurs at the edges of tissues with different T2 decay values.
  - Allows high effective TE → Increases T2 weighting
  - Reduces slice number per TR
  - Increased image blurring
- The Shorter turbo factor
  - The Longer scan time
  - Allows low effective TE → Increases T1 weighting
  - More slices per TR
  - Reduced image blurring



Uses of fast spin echo:

- Similar to spin echo (useful in most clinical applications):
  - In the central nervous system, pelvis and musculoskeletal regions, fast spin echo has now largely replaced spin echo.
  - In the chest and abdomen respiratory artifact is sometimes troublesome (why?)





Weighting in fast spin echo

- T1 weighting
  Short effective TE less than 20 ms
  Short TR 300–600 ms
  Turbo factor 2–6

- T2 weighting
  Long effective TE 100 ms
  Long TR 4000 ms+
  Turbo factor 8–20

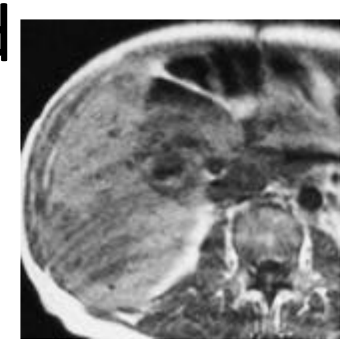
- Proton density/T2 weighting
  Short effective TE 20 ms/long effective TE 100 ms
  Long TR 2500 ms+
  Turbo factor 8–12

Advantages of fast spin echo

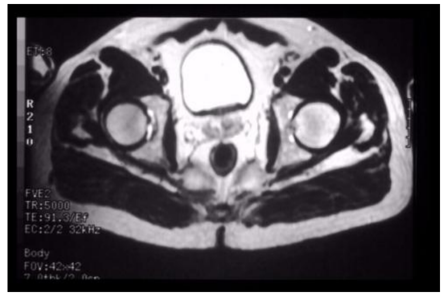
- Reduced scan times
- Higher resolution (↑matrix size with no ↑ in imaging time)
- Improved image quality (↑ NEX with no ↑ in imaging time)
- Increased T2 formation

Disadvantages

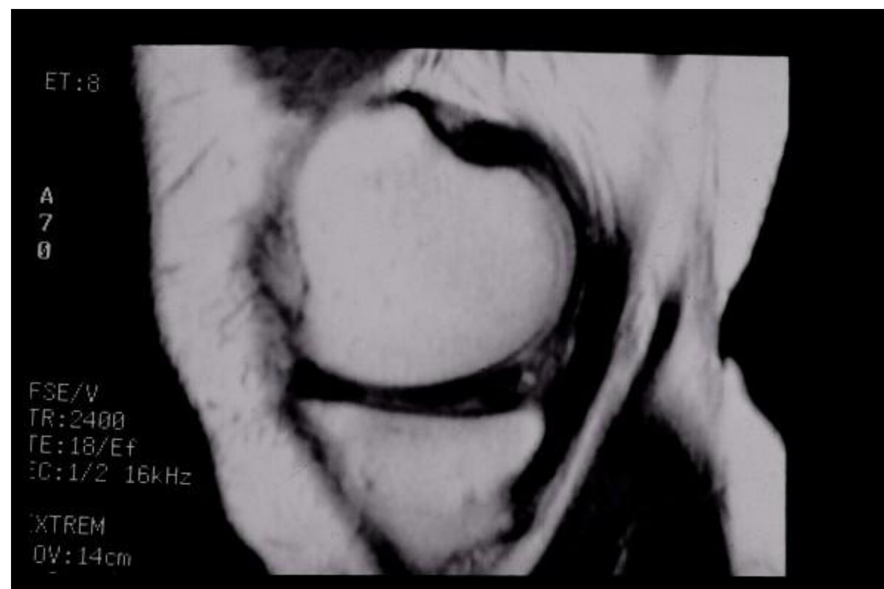
- Some flow and motion effects increased



- Fat bright in T2



- Image blurring (different TE)



- Reduce magnetic susceptibility artifacts

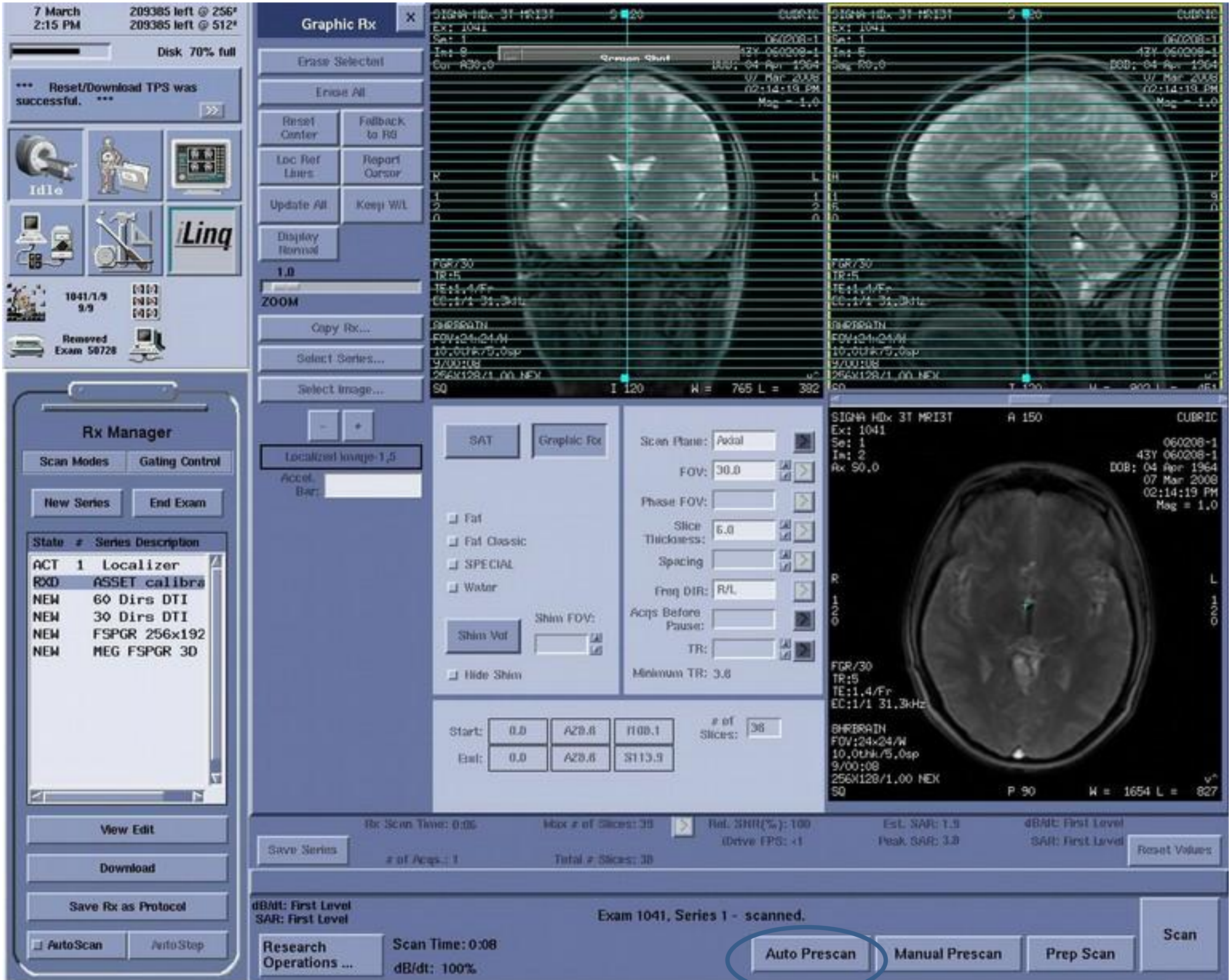
Note

N.B. other ways to decrease imaging time one of the following can be done:

- Decreasing the TR → affects image weighting ☹
- Decreasing the NEX → affects SNR ☹
- Reducing the number of phase encodings → reduces spatial resolution ☹

PRE-SCAN

Definition: a method of calibration that should be performed automatically before every data acquisition.



Tasks:

1) Finding the centre frequency on which to transmit RF.
   – This is usually chosen to be the resonant frequency of water protons (but can be adjusted to centre on the fat protons).
2) Finding the exact magnitude of RF transmitted to generate maximum signal in the coil.
   – = energy required to flip the NMV through 90^{o}.
   – Consequently, the system can calculate how much energy is required for other flip angles
   – Called power spectrum or transmit gain
3) Adjustment of the magnitude of the received signal so that it is neither too large (leads to distortion), nor that it is too small (cannot be properly detected above the background noise)

- **Varies with each patient → should be performed before every acquisition of data**

Types of acquisition

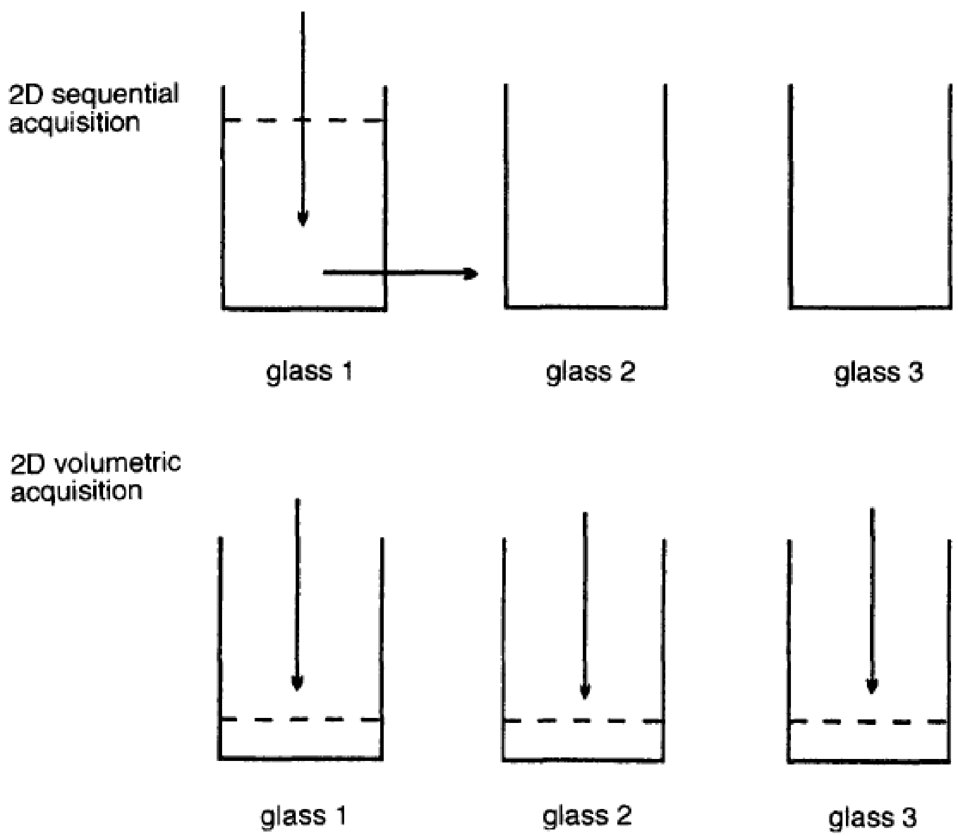
There are basically three ways of acquiring data:

(1) Sequential acquisitions:

- acquire all the data from slice 1 and then go on to acquire all the data from slice 2, (all the lines in K-space are filled for slice 1 and then all the lines of K space are filled for slice 2, etc.).

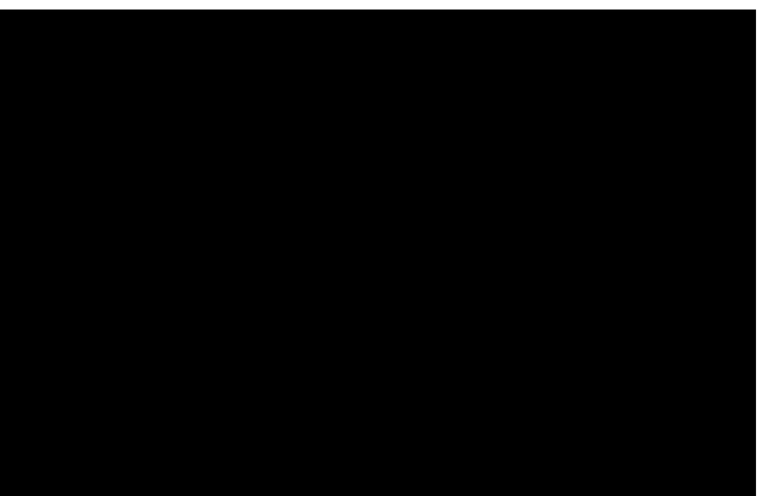
(2) 2D volumetric acquisitions:

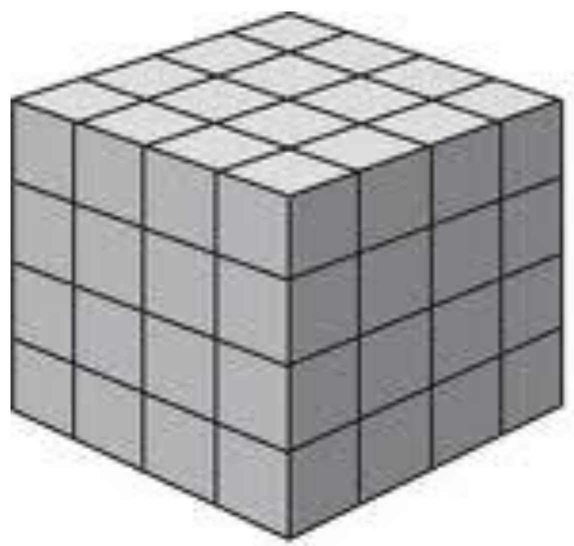
- fill one line of K space for slice 1, and then go on to fill the same line of K-space for slice 2, etc.
- When this line has been filled for all the slices, the next line of K space is filled for slice 1, 2, 3, etc.

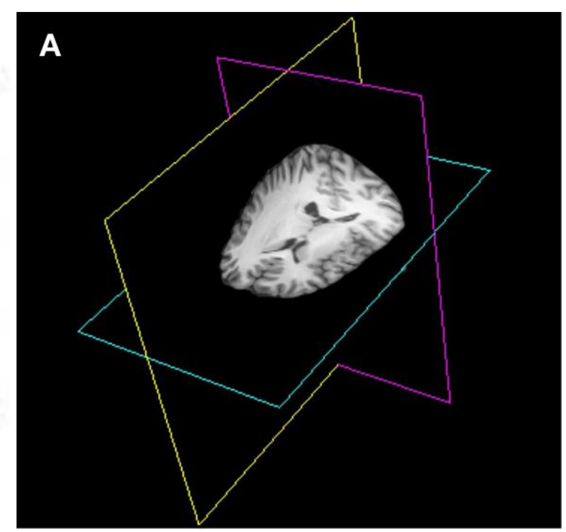


(3) Three-dimensional volumetric acquisition (volume imaging):

- Acquires data from an entire volume of tissue, rather than in separate slices.
- The excitation pulse is not slice selective, and the whole prescribed imaging volume is excited.

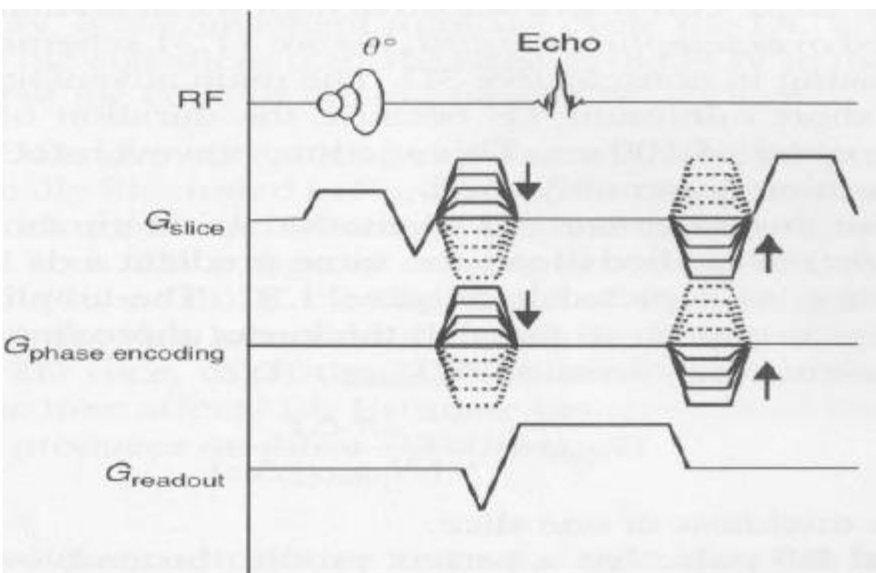


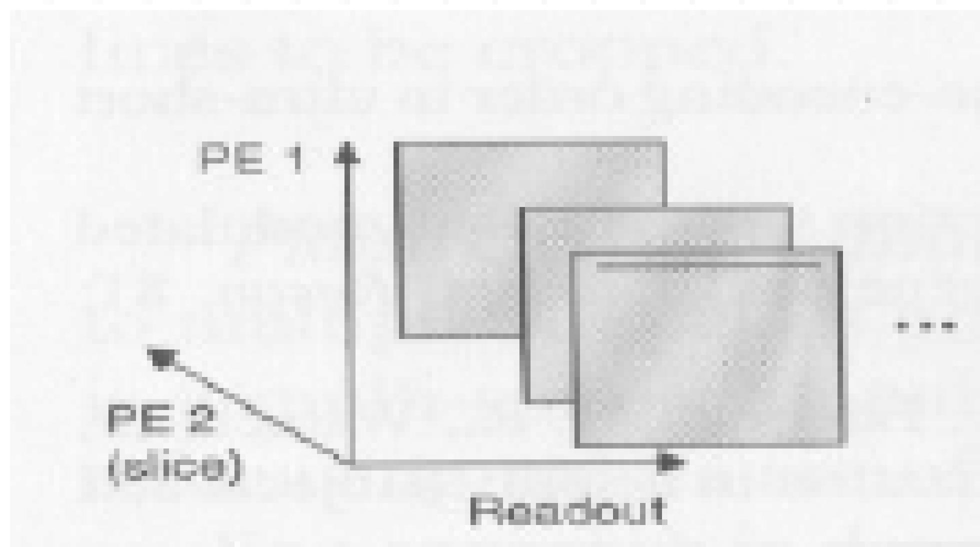




- After performing all phase encodings, the volume or slab is divided into discrete locations by the process of slice encodings:
  - The same as phase encoding steps
  - i.e. number of encoding steps increase →scan time is increased
  - i.e. scan time = TR x NEX x number of phase encodings x number of slice encodings

Compare with conventional imaging where number of slices does not affect scan time





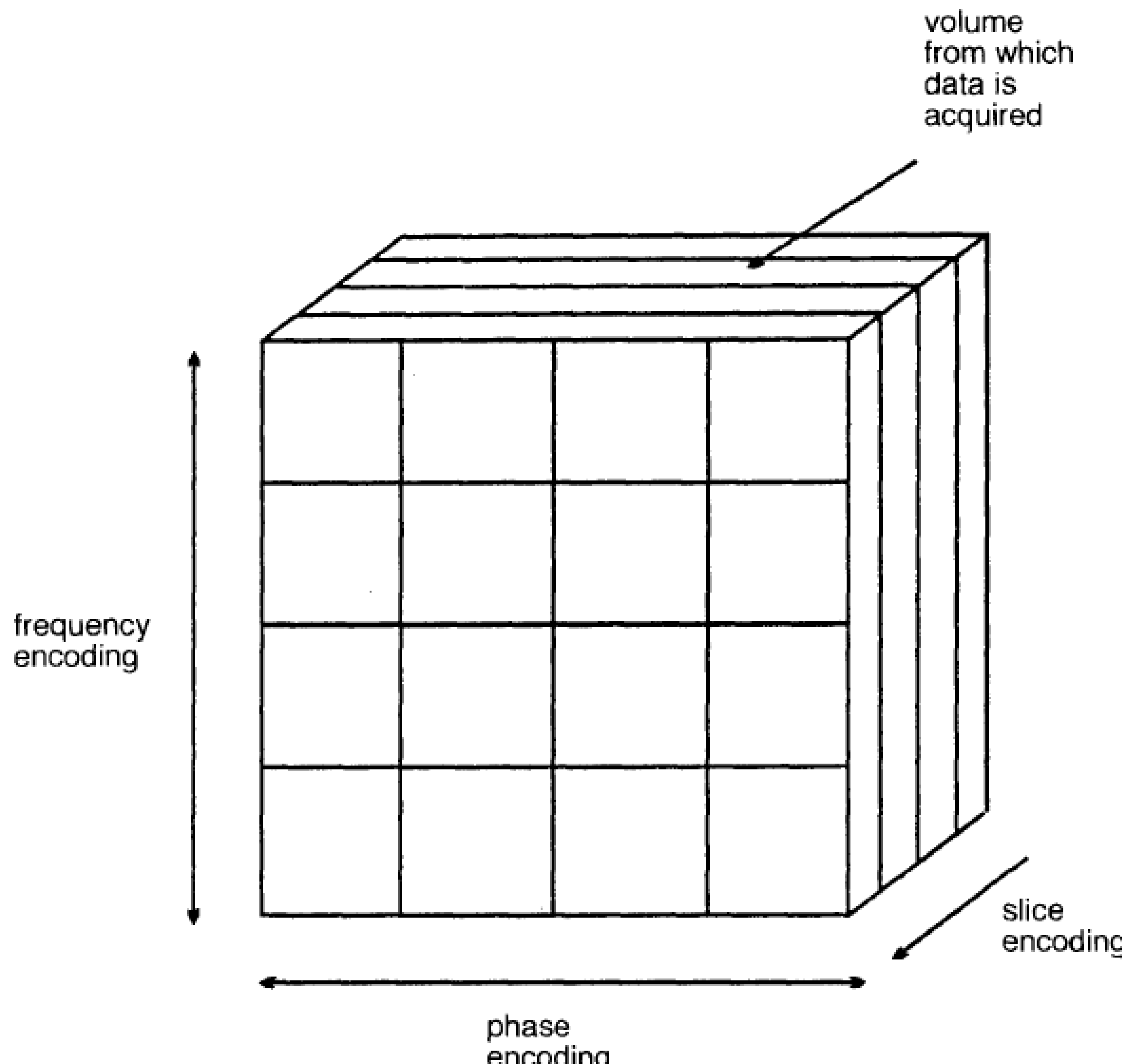
Advantages of volume imaging:

1) Very small lesions can be demonstrated (slice thickness can be markedly reduced &there are no slice gaps)
2) Entire volume is excited → SNR is superior → fewer NEX is required (compare to conventional imaging where slice thickness affects SNR)
3) Cuts can be manipulated to look at the volume in any angle of obliquity
4) Slice thickness can be reduced to produce isotropic imaging

Disadvantage of volume imaging:

Scan times are relatively long

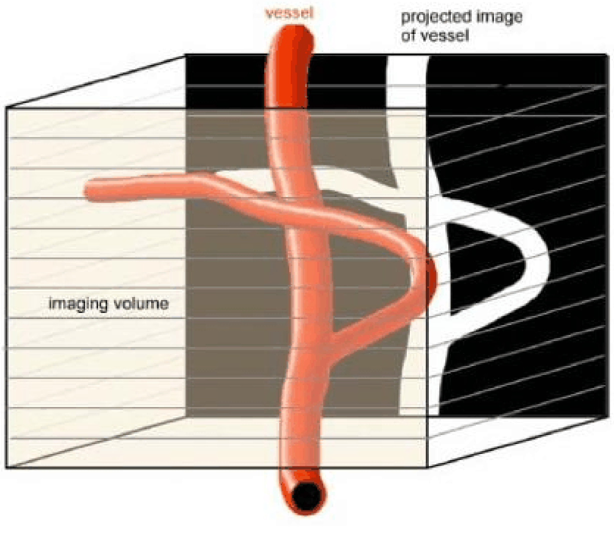
- So that must be used with fast pulse sequences
- This is somewhat offset by decreasing number of NEX required


volume
from which
data is
acquired
frequency
encoding
slice
encoding
phase
encoding

Uses of volume imaging:

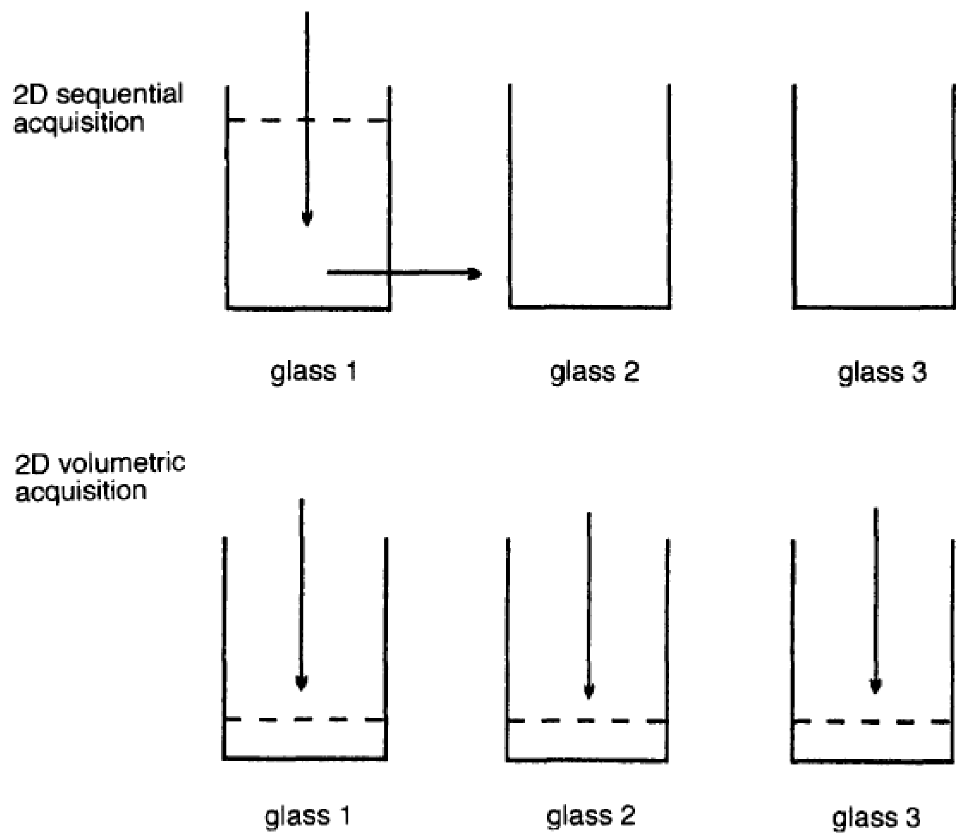
1) Joint imaging where anatomy (e.g. ligaments) is not strictly in plane and when I need thin slices
2) MRA (can be reconstructed in any plane)
3) When looking for small lesions

N.B: In volume imaging increasing slice number (volume) will increase SNR.



N.B:

- As multiple slices are selected during a 2D and 3D volumetric acquisition, movement during acquisition affects all the slices.
- During a sequential acquisition, movement of the patient only affects those slices that are acquired while the patient is moving.



Scan Parameters and Trade-offs

Signal to noise ratio (SNR):

Definition:

- Ratio of the amplitude of the signal received to the average amplitude of the noise.

Noise sources:

- White noise: patient's random thermal movements of H atoms
- Electronic noise: caused in the scanner
- Environment: caused by interference of RF pulse

- Noise is constant for every patient ,The signal however depends on many factors and can be altered.

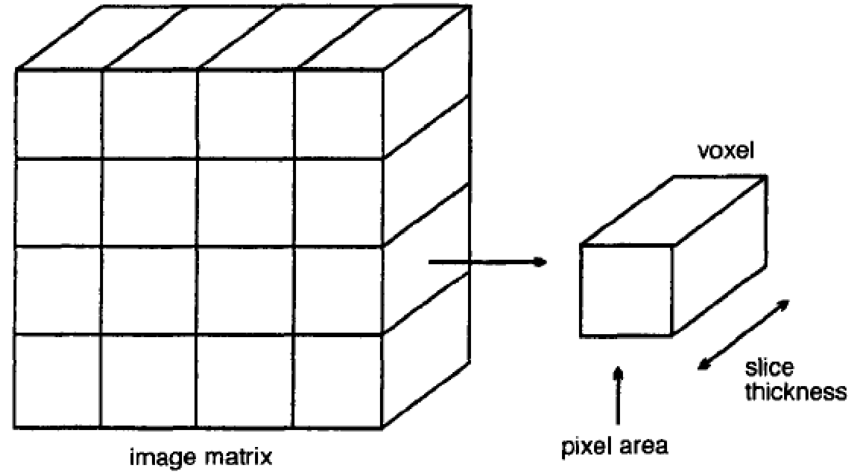
The factors that affect the SNR are:

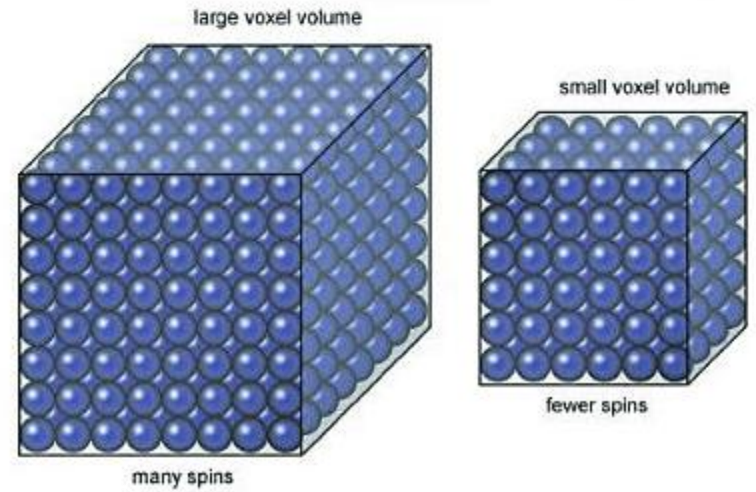
1) Proton density:

- Determines the amplitude of signal received.
- Areas of low proton density (e.g. lungs), have low signal and low SNR
- Areas with a high proton density (e.g. pelvis), have high signal and high SNR.

2) Voxel volume:

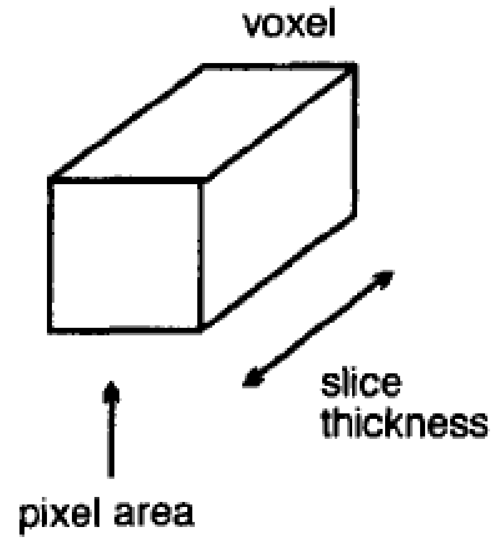
- Large voxels contain more spins or nuclei than small voxels, and therefore have a higher SNR than small voxels
- i.e. SNR α voxel volume





Voxel volume = slice thickness x pixel area

=slice thickness x FOV dimensions/ matrix size

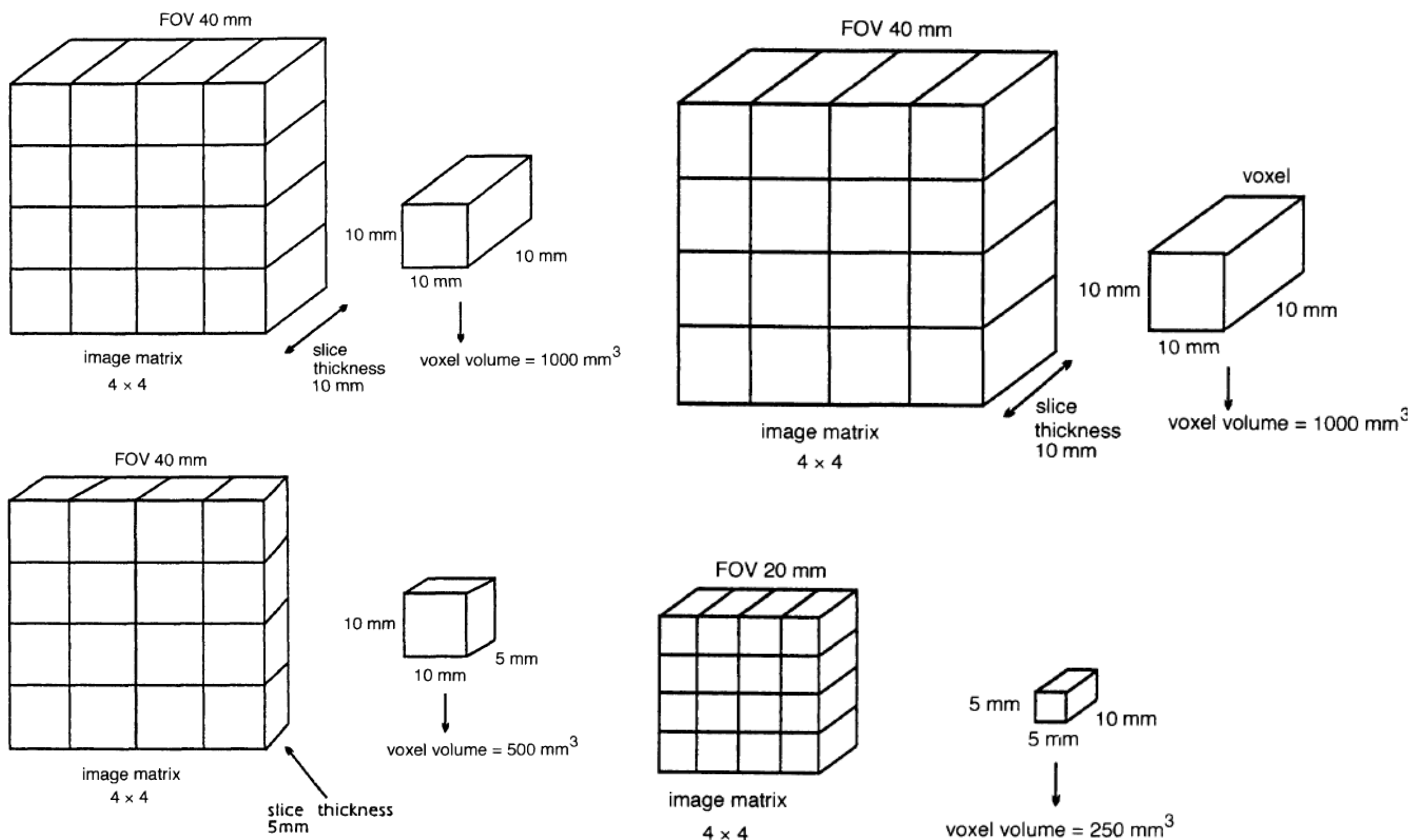


i.e.

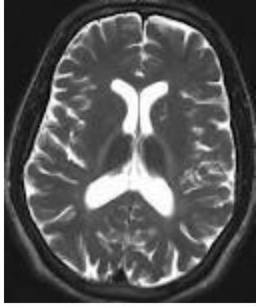
- SNR α slice thickness
- SNR α pixel area
- SNR α FOV^2
- SNR α 1/matrix size (e.g. 1/number of phase encodings)

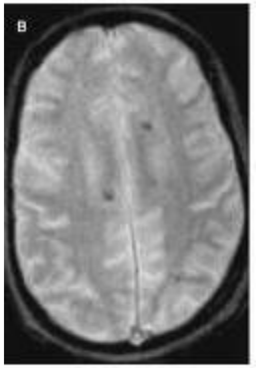
Examples:

- Doubling the phase encodings , halves the pixel dimension along the phase axis. This halves the voxel volume and the SNR
- Halving the FOV → the voxel volume and the SNR are reduced to a quarter of their original value



3) Type of pulse sequence

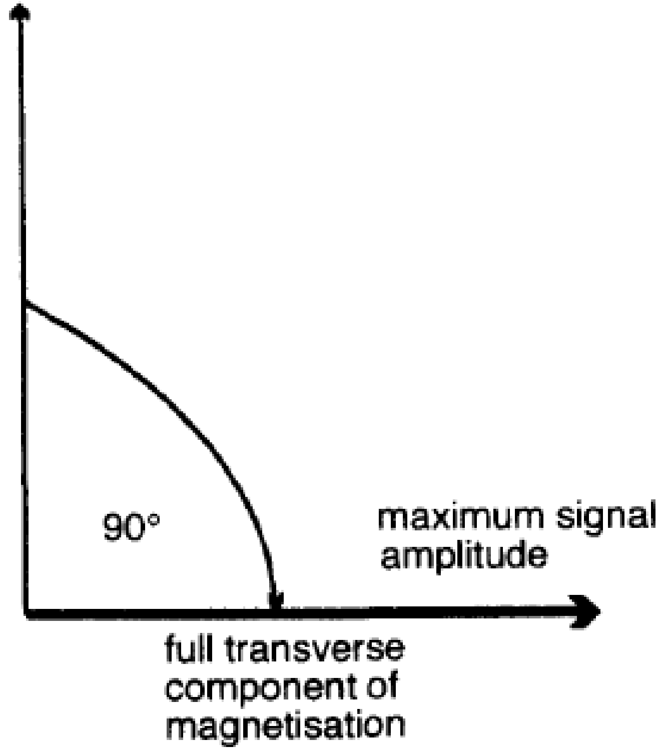


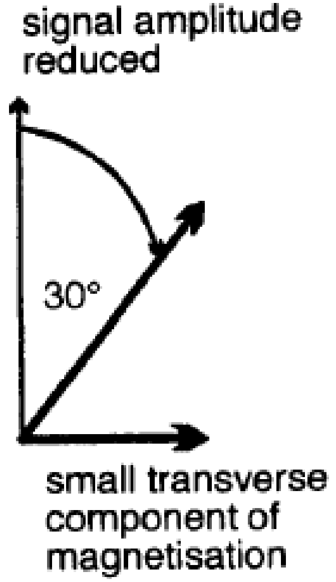


- Spin echo pulse sequences have more SNR than gradient echo sequences because:
  - All the longitudinal magnetisation is converted into transverse magnetisation by the 90° flip angle.
  - the 180° rephasing pulse is more efficient at rephasing than the rephasing gradient

4) The flip angle:

Flip angle controls the amount of transverse magnetisation →The lower the flip angle, the lower the SNR.

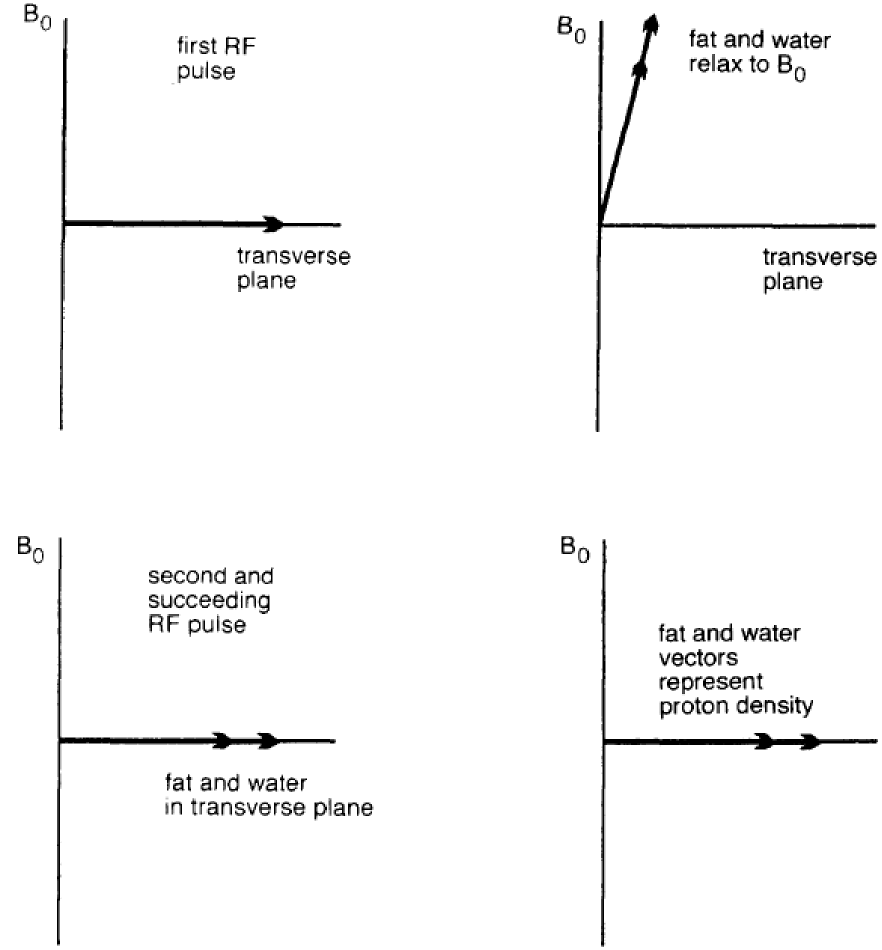




5-TR:

TR controls the amount of longitudinal magnetisation that is allowed to recover before the next excitation pulse is applied.

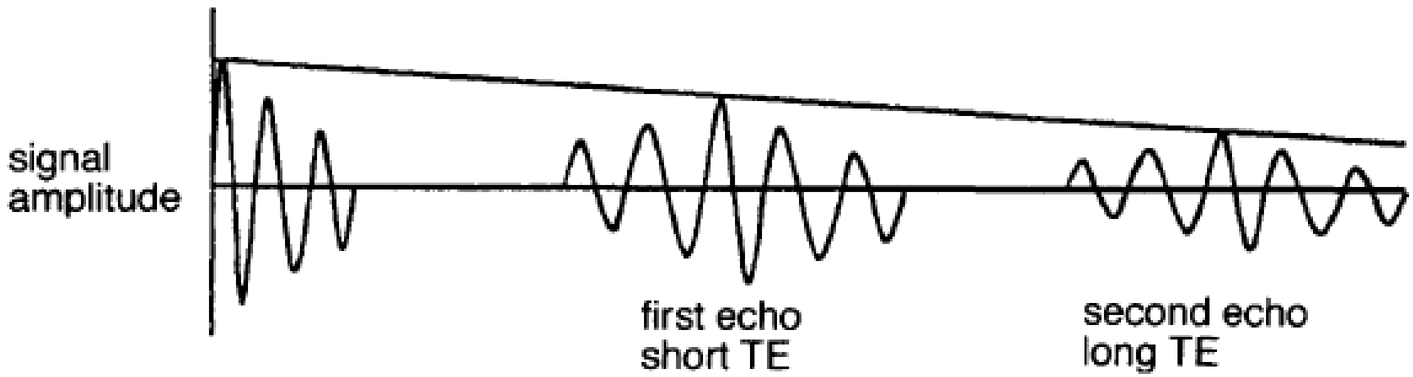
long TR →full recovery of the longitudinal magnetisation →more is available to be flipped To transverse plane in the next repetition → more SNR



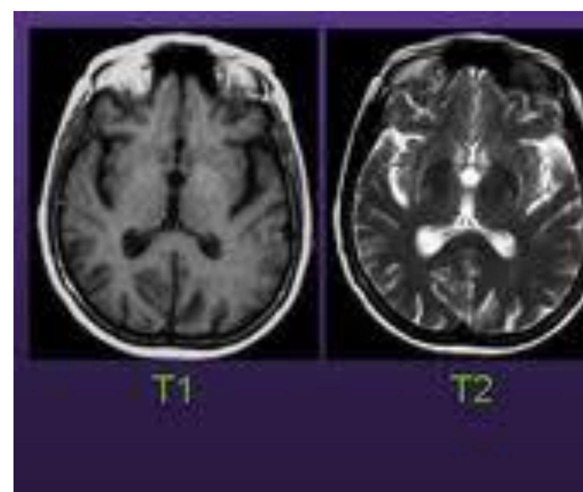
6- TE:

TE controls the amount of transverse magnetisation that is allowed to decay before an echo is collected.

long TE allows considerable decay of the transverse magnetisation → less SNR

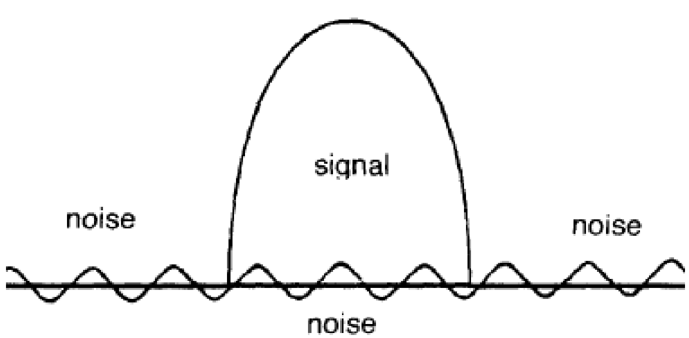


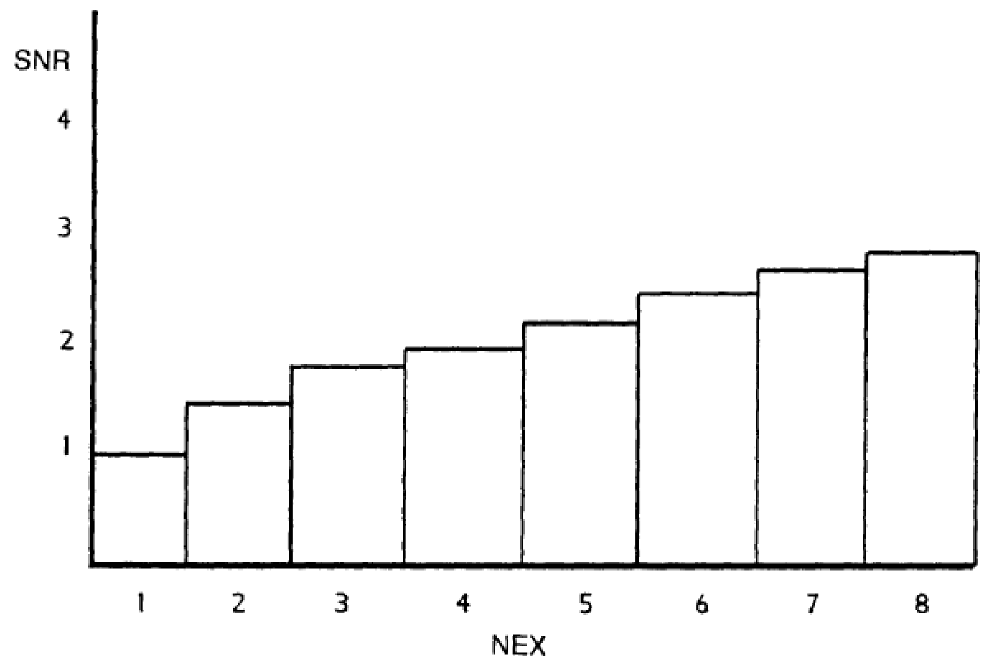
N.B. T2 weighted image often has a less SNR than a T1 weighted image (longer TE)



7) Number *of averages (NEX)*

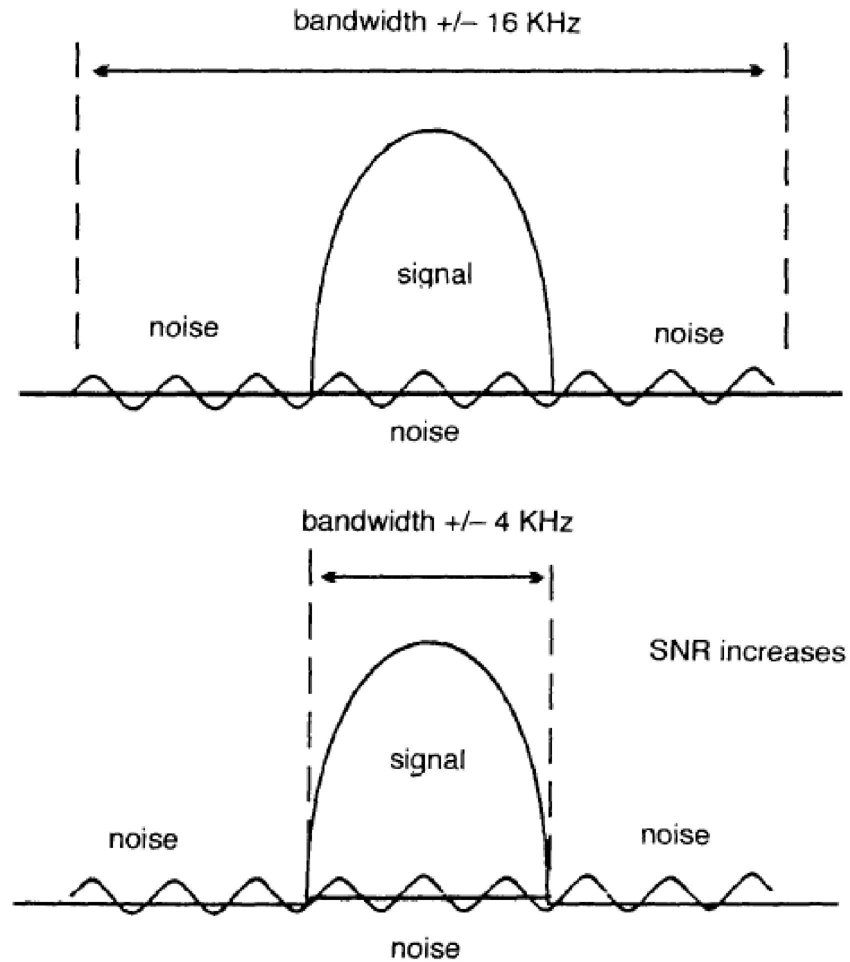
- = Number of times data is collected with the same amplitude of phase encoding slope.
  - Doubling the NEX therefore doubles the amount of data that is stored in each line of K space.
  - The data contains both signal and noise.
  - Noise is random , Signal however is not random→ doubling the NEX only increases the SNR by √2 *(= 1.4).*
  - *NEX can be increased in sella MRI (why?)*





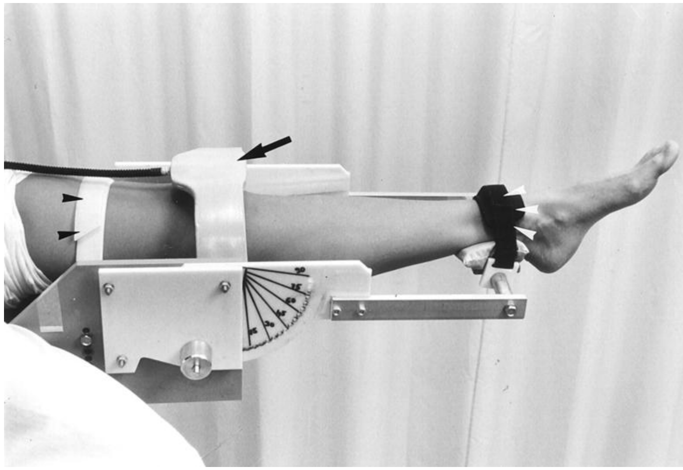
8) Receive bandwidth

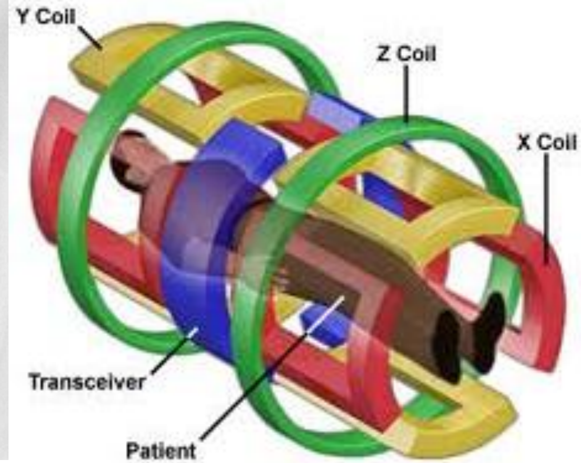
- =Range of frequencies that are sampled during the application of the readout gradient.
- Reducing the receive bandwidth results in less noise being sampled relative to signal.
- i.e. the SNR increases as the receive bandwidth decreases
- Halving the bandwidth:
  - Increases the SNR by 40%,
  - Increases the sampling time
  - Increases the minimum TE available



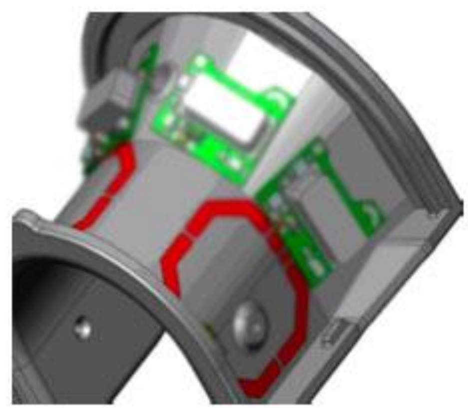
9) Type of coil

- SNR of:
  - ➢ Surface coils > body coil (placed close to the area under examination)





  - ➢Phased array coils > single coil (multiple coils are used to receive signal)



•In general, the size of the receiver coil should be chosen such that the volume of tissue imaged fills the sensitive volume of the coil.

Contrast to noise ratio (CNR)

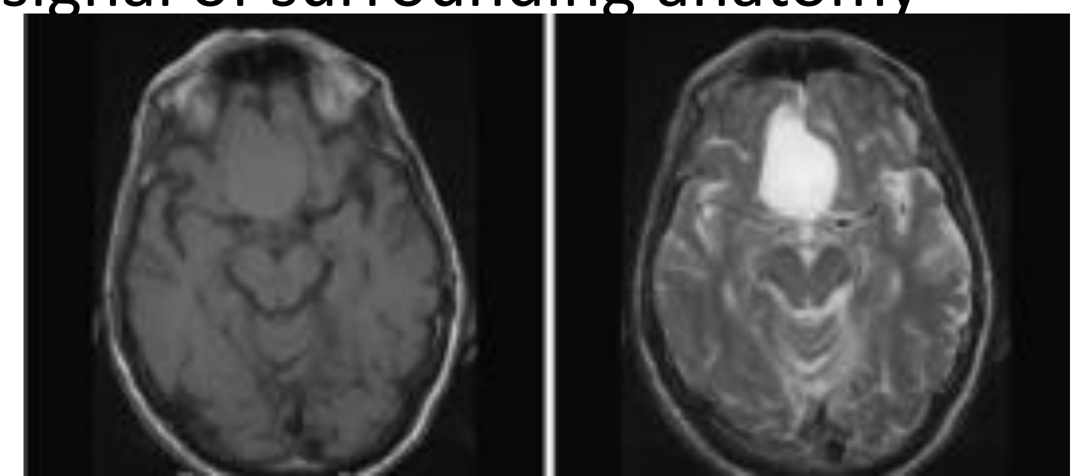
Definition:

- The difference in the SNR between two adjacent areas.
- Most critical factor affecting image quality

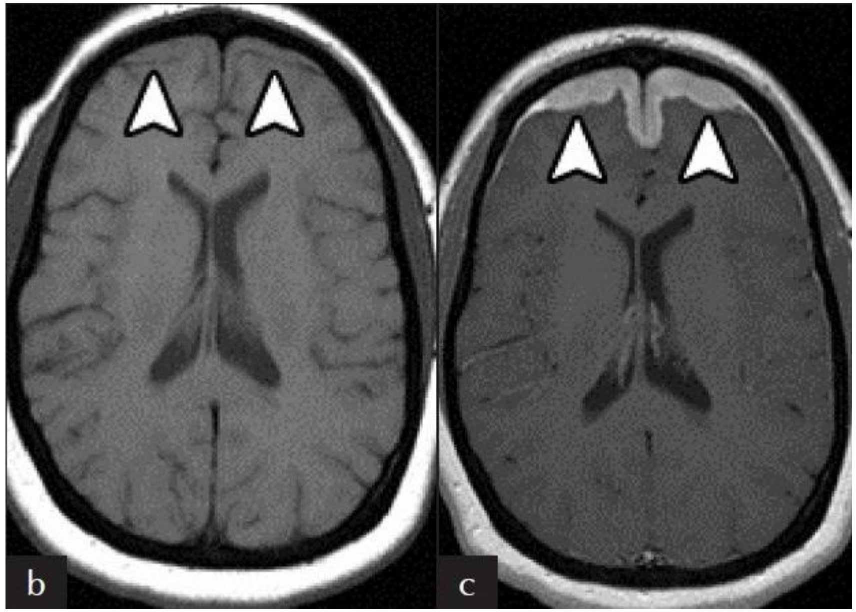
Factors affecting CNR:

1) T2 images has higher CNR the T1:

- The ability to distinguish tumour from normal tissue is greater because of high signal of the tumour compared to the low signal of surrounding anatomy



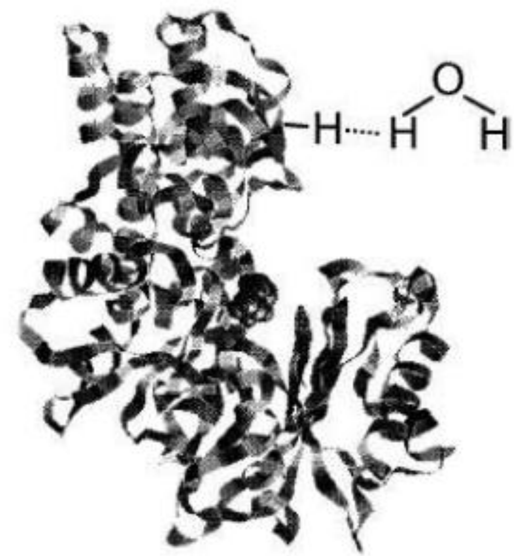
2) Administering contrast agents increase the CNR (pathology enhances)



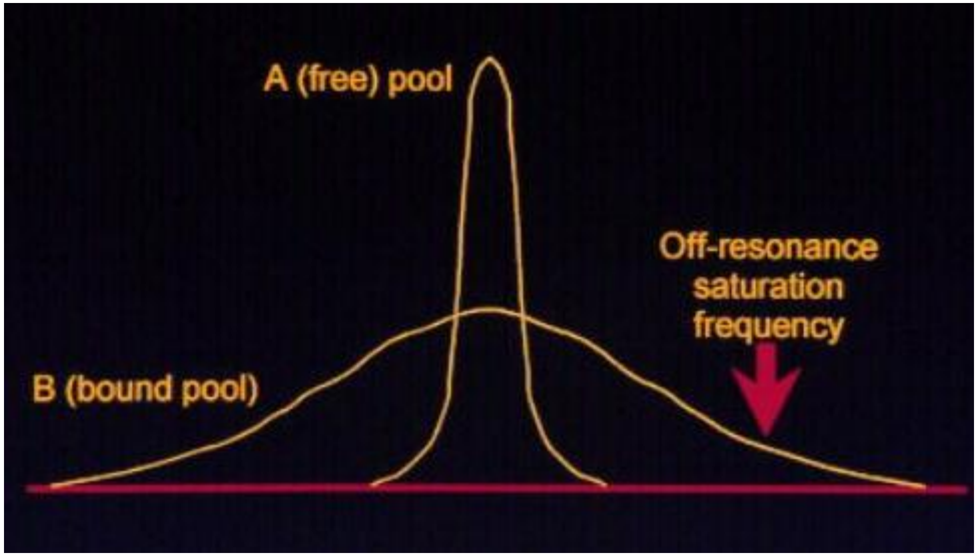
3) Fat suppression increase CNR

4) Magnetization transfer imaging:

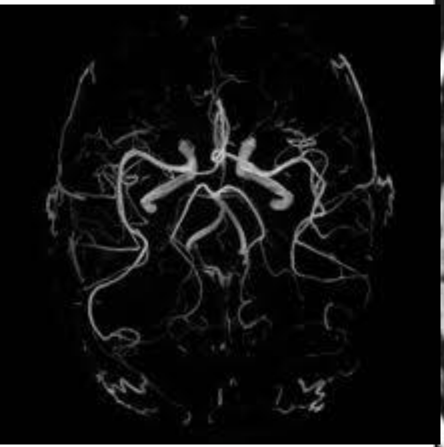
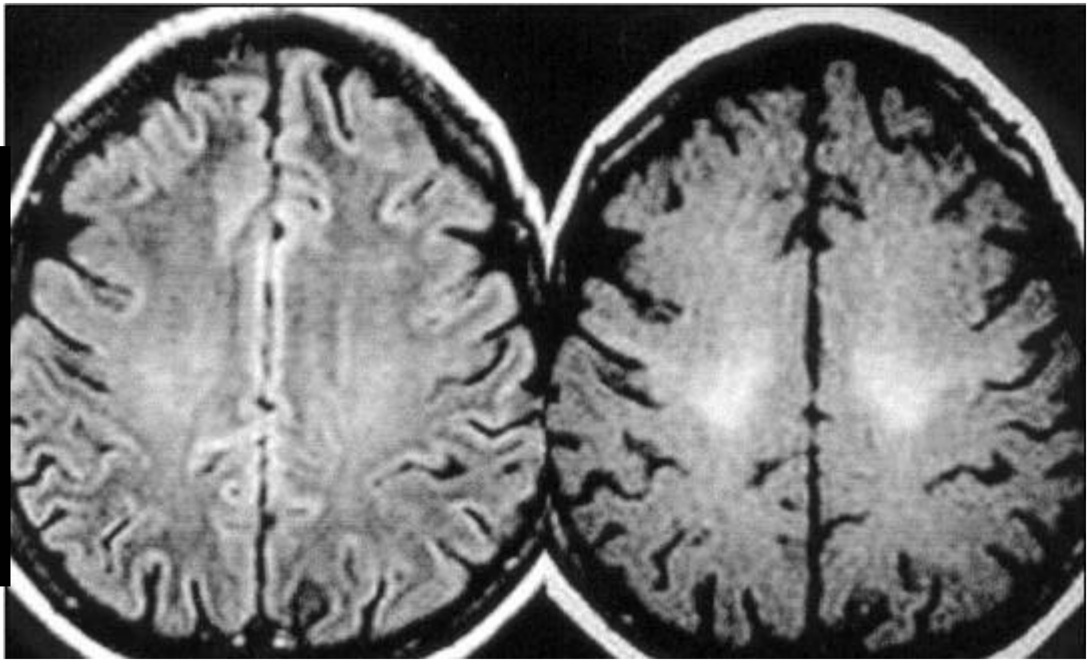
- There are two types of protons in normal tissues
  - Macromolecules (bound) protons:
    - Protons of large proteins
    - Transverse components decay before the signal can be collected and cannot be visualized.
  - Water (free) protons:
    - protons that have longer decay times can be visualized
    - May be coupled to macromolecules or not
- Magnetization Transfer Imaging (MTI) is based on the magnetization interaction between Macromolecules and coupled water protons.



- Applying an off resonance radio frequency pulse to bound protons→ selective saturation of bound protons → transfer of this magnitization to the coupled free protons →increase T1 time of free protons →Decrease signal of free protons
- T1 time of uncoupled water does not change → appear brighter

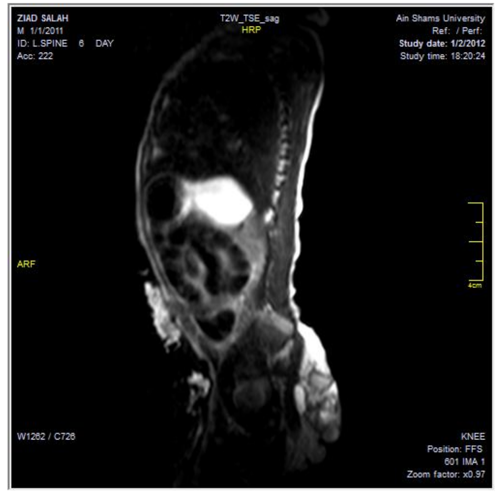


- Clinical uses of MTC imaging:
  - Contrast augmentation:
    - MR angiography (suppress tissues)
    - IV contrast enhanced images (MT of pathological tissues is less that normal tissues)
    - Joint imaging (increase contrast between cartilage and water)

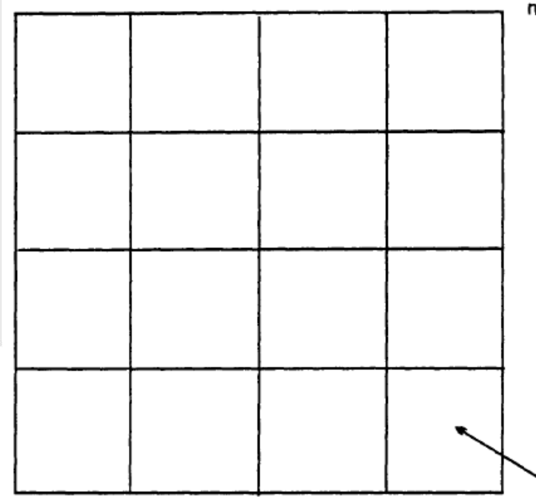




Spatial resolution

- **Definition:** ability to distinguish between two points as separate and distinct,
- controlled by
  1) voxel size:
    - Small voxels → good spatial resolution and less partial voluming
    - affected by:
    1) slice thickness: The thinner the slice → the more the resolution
    2) Pixel size: Small pixels increase spatial resolution , depend on
        – FOV: large FOV → large pixels → ↓ resolution
        – number of pixels or matrix.



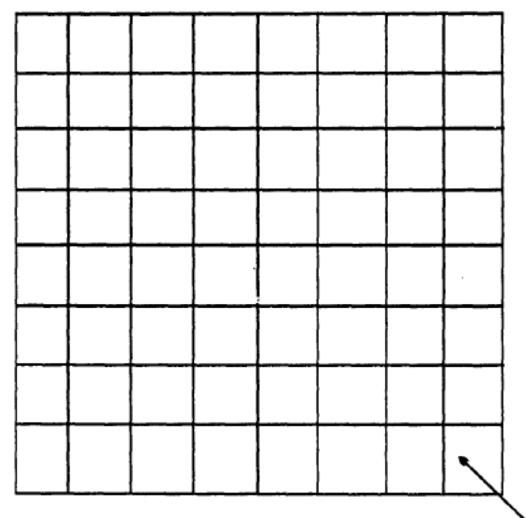
coarse matrix



large pixel

spatial resolution decreased

fine matrix

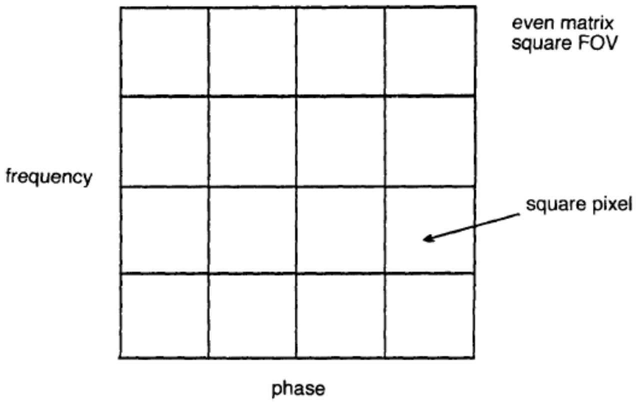


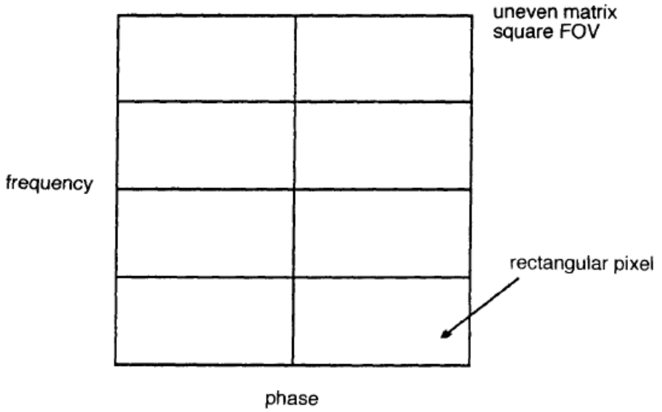
small pixel

spatial resolution increased

2) Pixel shape:

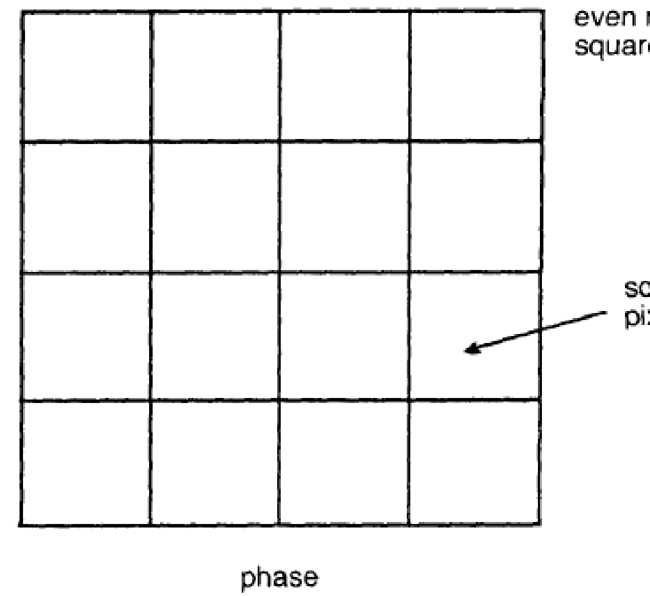
- Square pixels provide better spatial resolution than rectangular pixels as the image is equally resolved along both the frequency and phase axis.
- If an even matrix is selected, e.g. 256 x 256 →square FOV and square pixels
- If uneven matrix is selected (e.g. 256 x 128) two options are available:
  - <u>1) Systems producing square FOV and Rectangular pixels</u>
    - usually, the frequency number of the matrix is the highest number → pixels are longer in the phase direction→ spatial resolution is reduced along the phase axis but SNR is higher
    - Matrix determines the resolution and SNR

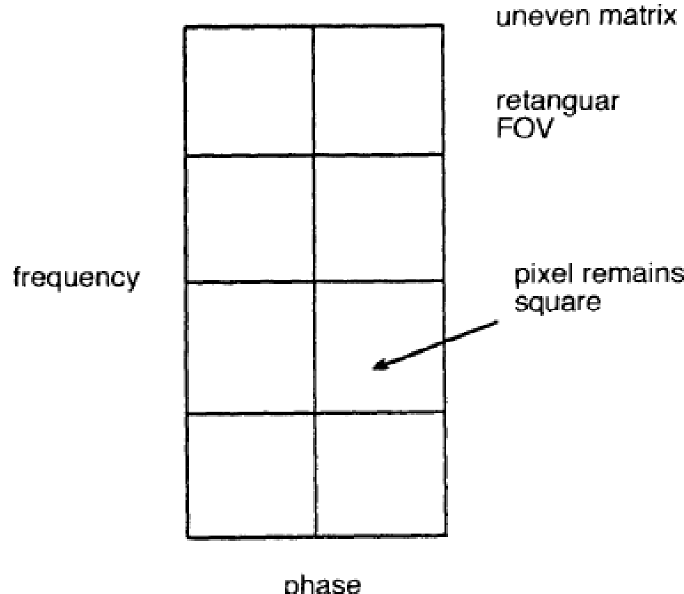




2) Systems producing square pixels and rectangular FOV:

- Therefore, if the number of phase encodings is half that of the frequency encodings, the FOV in the phase direction is half the size that it is in the frequency direction
- This method maintains the spatial resolution regardless of the matrix selected
- Result in less SNR and anatomy may not be covered
- To increase FOV phase encodings must be ↑, and this ↑the scan time
- Matrix determines the FOV
- Resolution and SNR is constant





N.B:

- In some cases, a rectangular FOV may be desired.

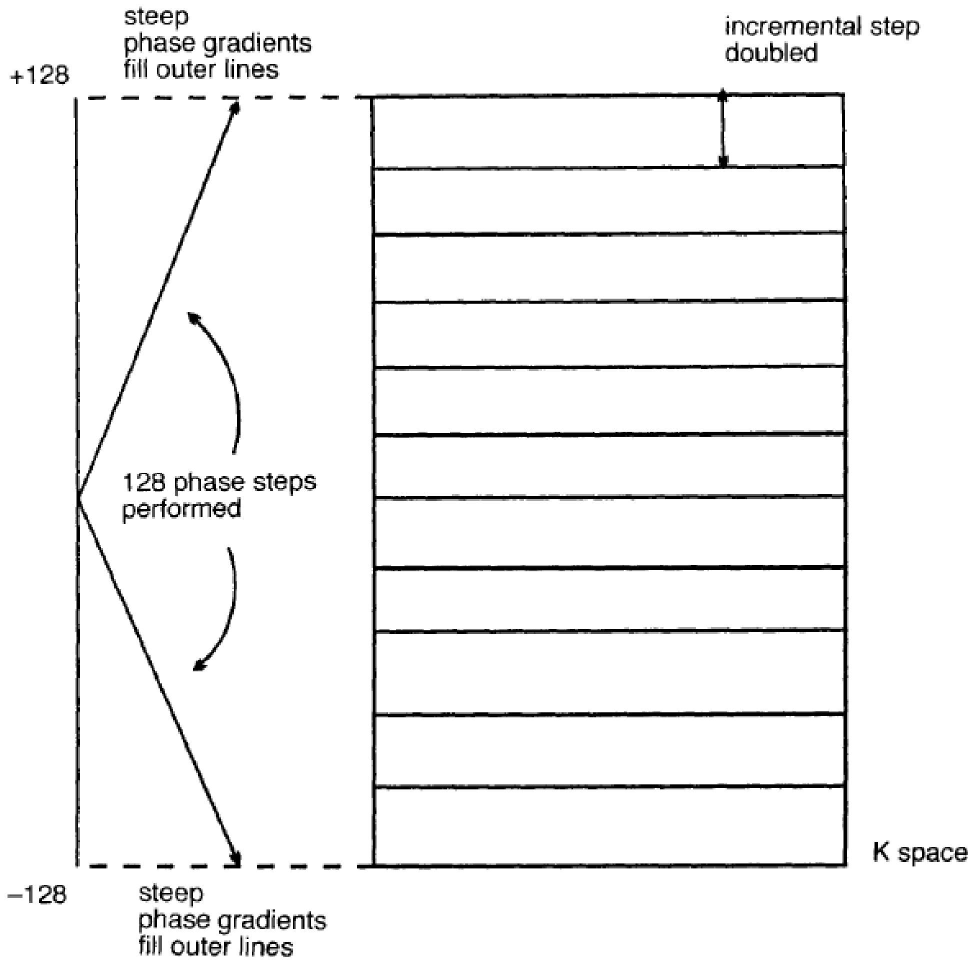
Example: sagittal lumbar spine image.

→Only half the number of phase encodings are performed

→ This maintains spatial resolution and halves the scan time

N.B. Rectangular FOV & K space filling

- If a 256 x 128 matrix has been selected, only 128 phase encodings must be performed
- The steep phase gradients (+128 and -128) must be performed also to increase resolution
- We do this by performing phase encodings between +128 and -128 with doubling The increment between each phase encoding step so that only 128 phase encodings need to be performed and the size of the FOV is halved in the phase direction And the scan time is halved



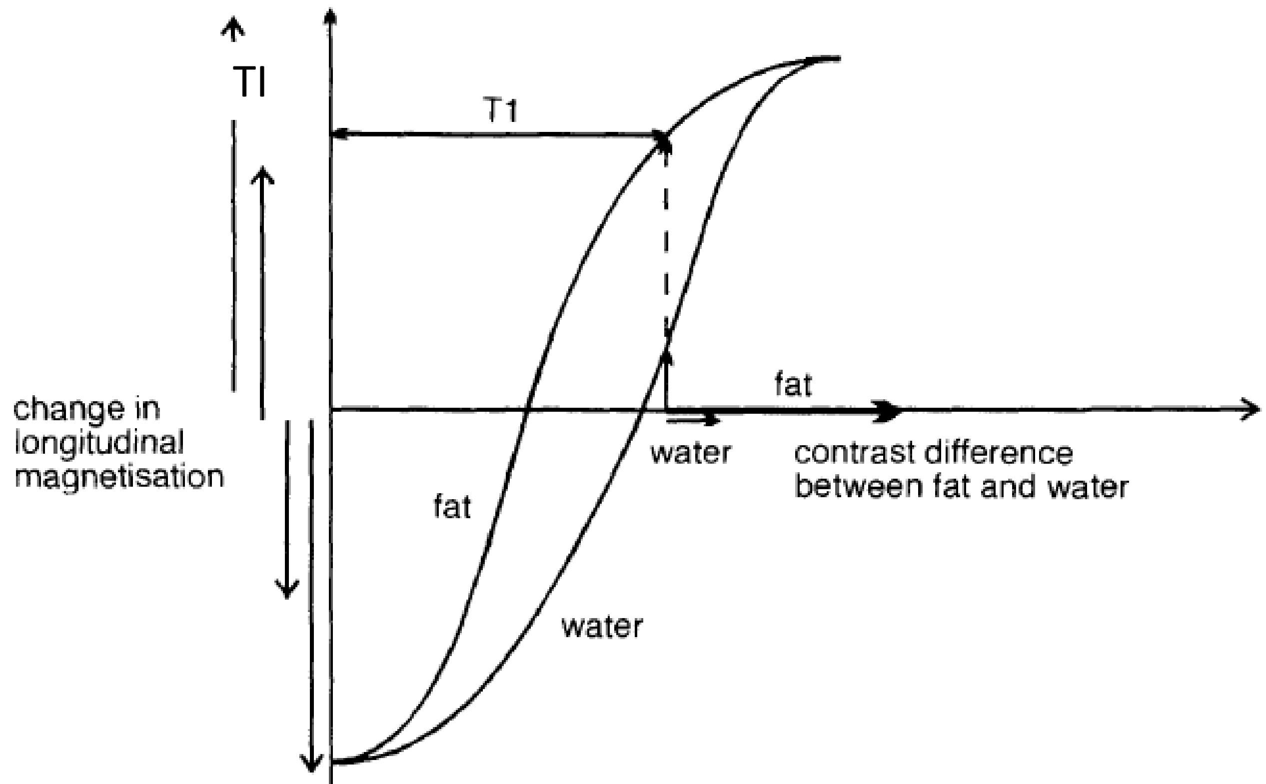
Note about the Steep gradients:

- Gradient slopes have to be steep with thin slices, fine matrices or a small FOV (why?)
- Steep gradients have greater rise times (*time required for it to achieve the* correct slope).
- Therefore Steep gradient slopes:
  - Increases the minimum TE
  - Result in fewer slices being available.

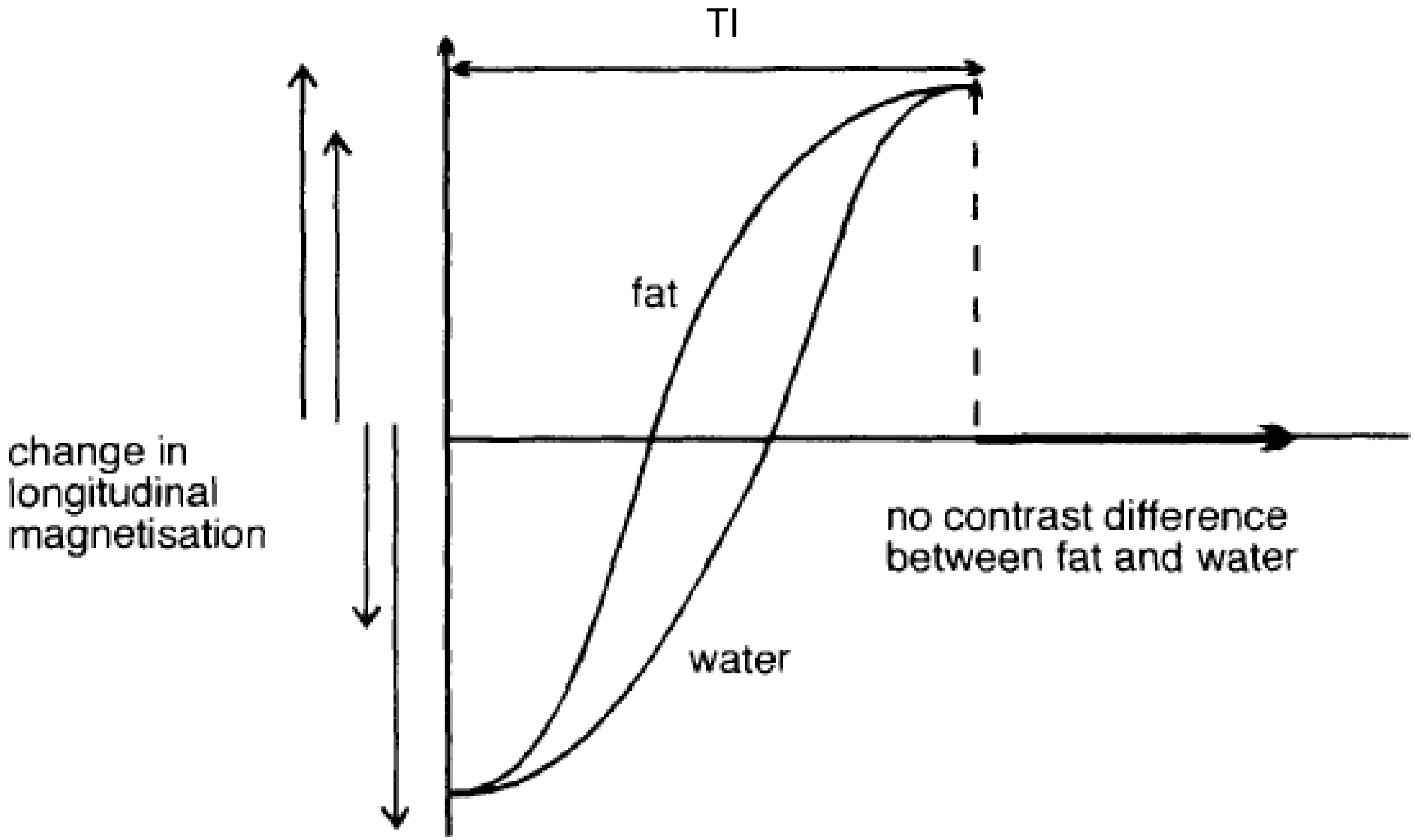
Inversion recovery pulse sequence

Sequence

1) 180⁰ inverting pulse is applied at the beginning →NMV is inverted into full saturation
2) When 180⁰ is removed → NMV begin to return to Bo
3) A *90⁰ excitation pulse is then applied at a time from the 180⁰ inverting* pulse known as the *TI (time from inversion).*
4) *The contrast of the resultant* image depends primarily on the length of the TI. If the *90⁰ pulse applied before full longitudinal recovery* → The resultant image is heavily T1 weighted (*180⁰ inverting pulse achieves full saturation and ensures* largest T1 contrast difference between fat and water).

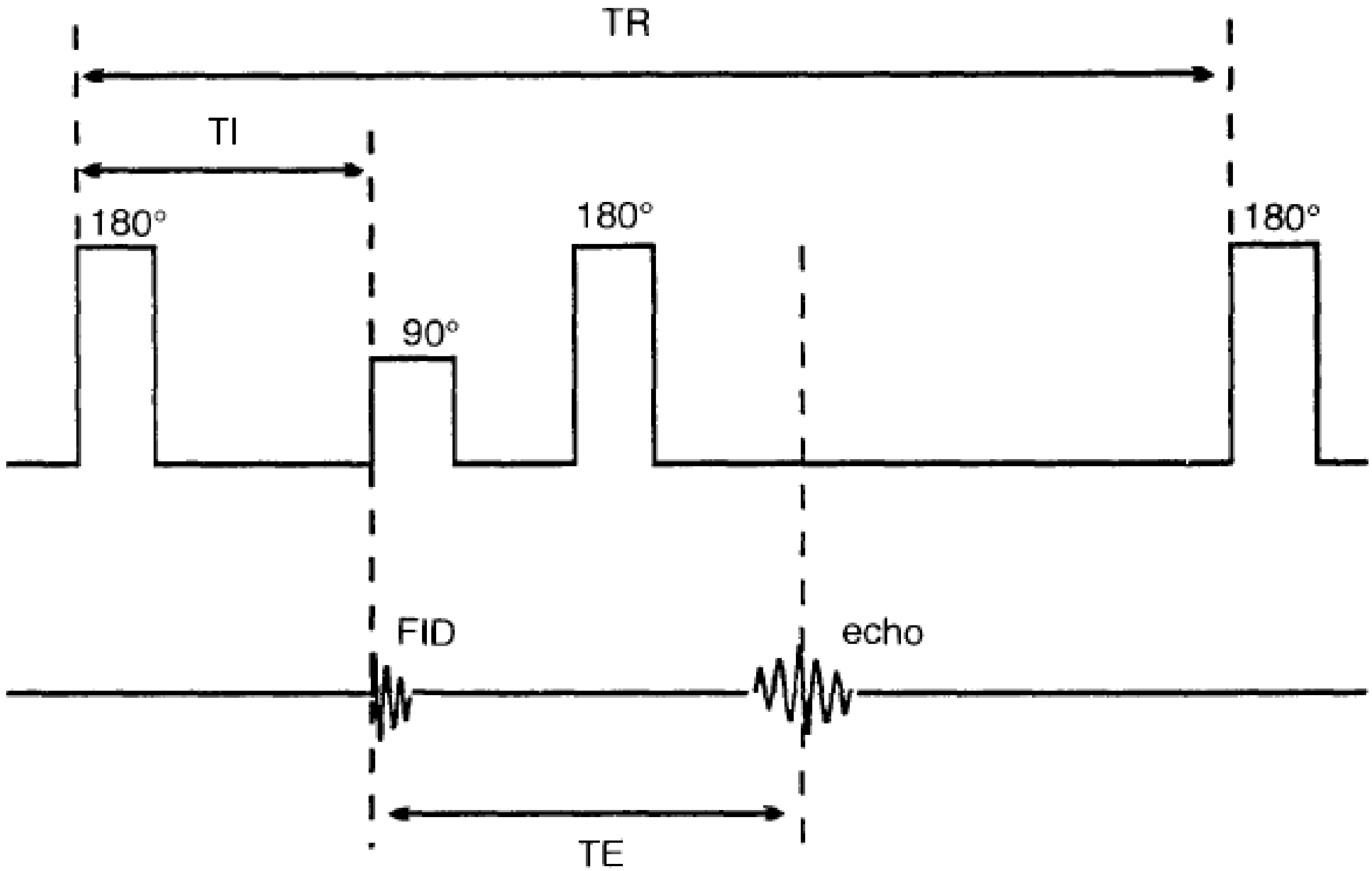


5) If the *90^o excitation pulse is not applied until the NMV has reached full* recovery → a proton density or T2 weighted image results, as both fat and water have fully relaxed



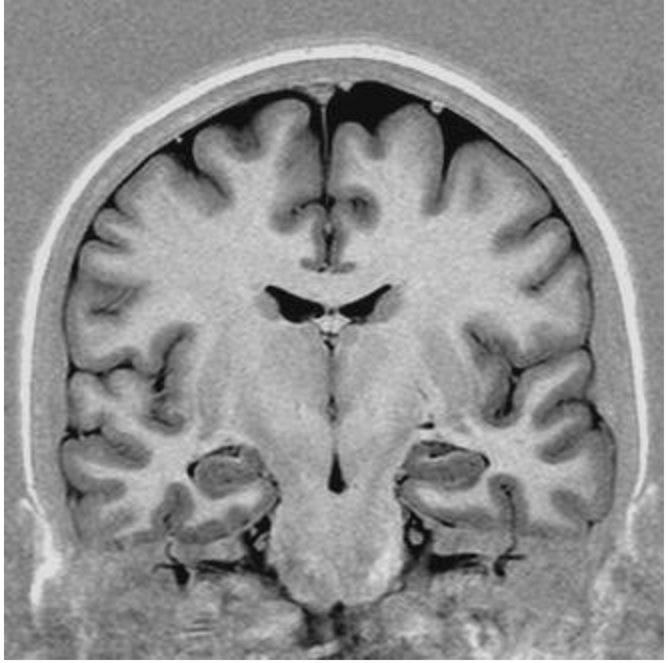
6) After the *90^o excitation pulse, a 180^o rephasing pulse is applied at a* time TE to produce a spin echo.

7) TR is the time between each *180^o inverting pulse*



Parameters of inversion recovery pulse sequence:

- TR:
  - should always be long enough to allow full recovery of the NMV before the next inverting pulse is applied (should be longer than 2000 ms)
- TE:
  - When used to produce heavily T1 weighted images TE is kept short to minimise T2 effects.
- TI:
  - The most potent controller of contrast in the inversion recovery sequence.
  - Medium TI values give T1 weighting but, as this is lengthened, the image becomes more proton density weighted.



Advantages of inversion recovery pulse sequence:

- Very good SNR as the TR is long
- Excellent T1 contrast

Disadvantages:

- Long scan times unless used in conjunction with fast spin echo

summary

Proton density weighting

- Long TI: 1800 ms
- Short TE: 10-20 ms
- Long TR: 2000 ms+
- Average scan time: 5-15 min

T1 weighting

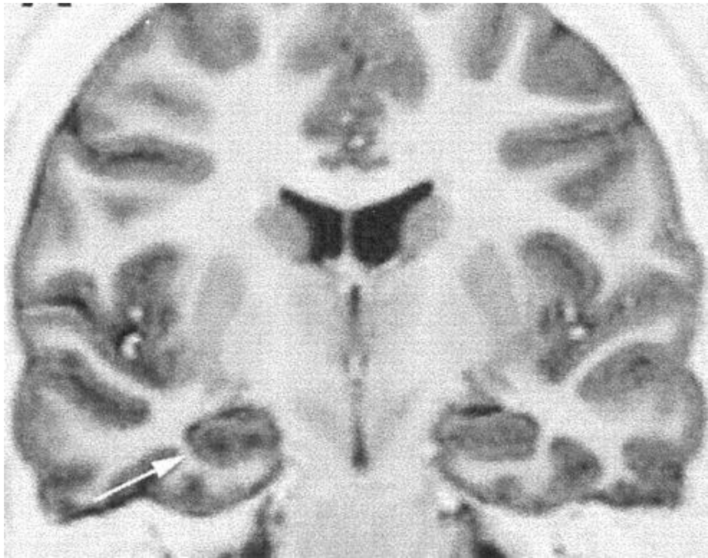
- Medium TI: 400-800 ms
- Long TE: 70 ms+
- Long TR: 2000 ms+
- Average scan time 5-15 min

N.B:

Inversion recovery was conventionally used to produce heavily T1 weighted images to demonstrate anatomy. (IR pulse sequences produce more heavy T1 weighting than conventional spin echo)

IR pulse sequences also ↑signal from enhanced structures after contrast injection (contrast shorten T1)

IR sequences are now more widely used to produce STIR and FLAIR images



STIR (short TI inversion recovery)

Definition:

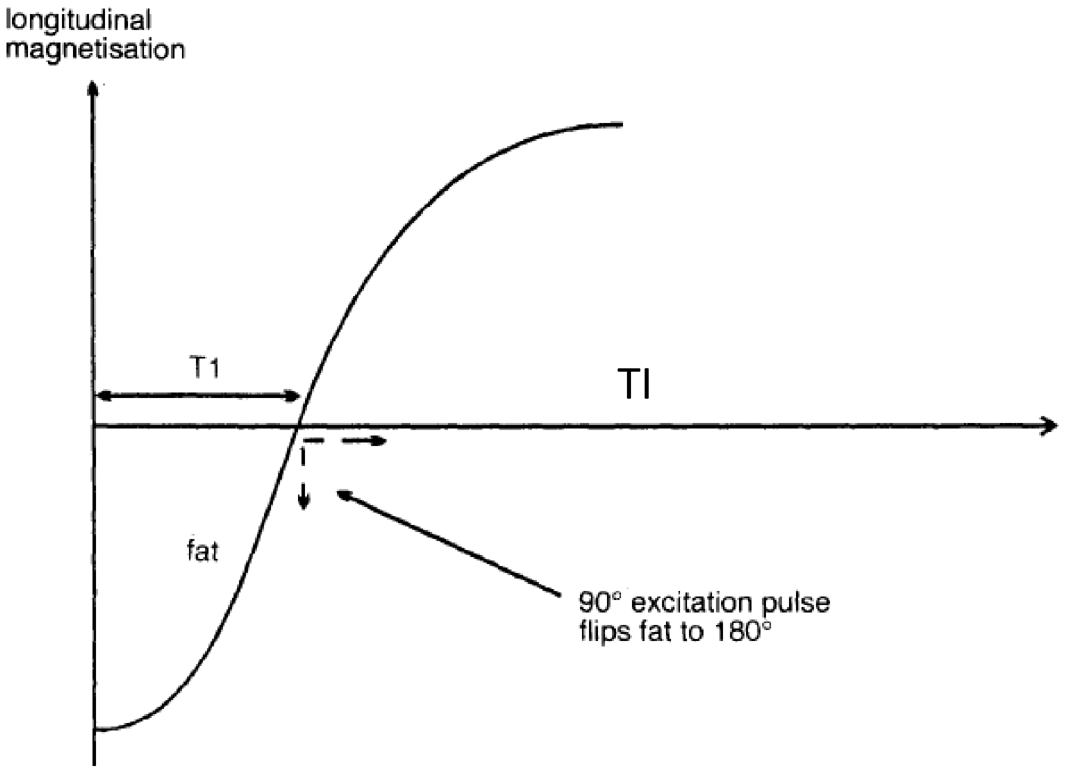
Inversion recovery pulse sequence that uses a TI that corresponds to the time it takes fat to recover from full inversion to the full transverse plane (at 90º)

Idea:

After this TI When the 90° excitation pulse is applied, the fat vector is flipped through 90° to 180° (into full saturation) , so that the signal from fat is nulled (no transverse component of magnetisation).

Use:

To achieve suppression of the fat signal in the image.



TI required to suppress fat:

- = 0.69 x T1 relaxation time of the fat =100-175 ms (although this value varies slightly at different field strengths).

Caution:

- should not be used in conjunction with contrast enhancement which shortens the T1 times of enhancing tissues (→ making them bright)
- The T1 times of these structures become close to the T1 time of fat. → enhancing tissue may also be nulled

STIR Parameters

- Short TI 150-175 ms
- Short TE 10-30 ms
- Long TR 2000 ms+
- Average scan time 5-15 min
- This sequence can also be used in conjunction with fast spin echo:
  - 180^{o} inverting pulse is followed by a 90^{o} excitation pulse after a short TI, and this in turn is followed by the echo train of 180^{o} rephasing pulses Therefore the scan time is considerably reduced
  - It is mainly used with a long turbo factor and TE to produce T2 weighting with fat suppression so that the appearance of water is enhanced.

FLAIR (fluid attenuated inversion recovery)

- In FLAIR, the signal from CSF is nulled by selecting a TI corresponding to the time of recovery of CSF from *180° to the transverse plane*
- TI used = O.69 x T1 relaxation time of CSF = 1700-2200ms (although this varies slightly at different field strengths)

Parameters:

- Long TI: 1700-2200 ms
- long TE to produce T2 weighting
- Long TR 6000 ms+
- Average scan time 13-20 mins


Thank You